Ecole Polytechnique fédérale de Lausanne

Master Thesis

Variability of Rainfall in a Semi-Arid Catchment in Burkina Faso

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Abstracts

The climate in the Sahel is marked by the spatial and temporal variability of rainfall. As the agriculture is mainly rainfed in Burkina Faso, the information about rainfall is crucial to help the farmers in their decisions. A network of wireless sensorscope stations is installed in the catchment of the Singou River (in the Gourma region of Burkina Faso) and monitor at a time step of 5 minutes meteorological parameters such as rain.The raindata of 2010 was evaluated and unreliable stations were excluded from the dataset. The rain events for the period of May to August were identified. More rain is measured in the month of August, which is rather due to thr higher frequency of rain events than to the intensity of the events. The accuracy of the Davis and précis rain gauges was evaluated through outdoor and laboratory experiments. At low intensities, the proposed error range for the Davis raingauges is +-15% and for the précis rain gauge data a correction factor of 2 (multiplication) should be applied. Indigenous knowledge was integrated in the thesis through a survey on the perception of rain in Tambarga. The most important aspects of rain are the quantity, the regularity of rain events and wind (which may destroy houses). The conditions that favour the development of a storm are analyzed through principle components analysis (PCA). The analysis showed that only few events are clearly influenced by one single parameter (soil moisture, latent heat flux, sensible heat flux, antecedent rain). The persistence of rainfall patterns was also subjected to analysis. A certain persistence of the rainfall patterns was detected for the month of August during which the rain events succeed closely each other. Finally, the validity of the formula of time of ponding based on Richard's equation was evaluated (using the data from the infiltration experiments). The formula is valid for the catchment only in the case when continous flow in the river is observed without the contribution of rain.

The results of the different analyses presented in the thesis give different insights on the characteristics of the rain events. Some information can already be used, but in order to obtain more meaningful results the analyses can be repeated with data that covers several years.

Le climat dans la zone du Sahel est marqué par une grande variabilité spatiale et temporelle de la pluie. Du fait que l'agriculture est essentiellement pluviale au Burkina Faso, l'information sur la pluie est cruciale pour soutenir les paysans dans leurs décisions. Un réseau de stations sensorscope a été installé dans le bassin versant de la Singou (Gourma BF) pour mesurer des paramètres météorologiques (comme la pluie) à un pas de temps de 5 minutes. Les données de pluies de 2010 ont été évaluées et les stations non fiables ont été exclues de la base de données. Les événements de pluies concernant la période de mai jusqu'à août ont été identifiés. Une plus grande quantité de pluie a été mesurée pour le mois d'août comparé aux autres mois. Ceci est du à la plus grande fréquence des pluies et non pas à leur intensité. La précision de mesure des pluviomètres Davis et précis a été évaluée par plusieurs expériences effectuées sur le terrain et dans le laboratoire. Pour des faibles intensités, la marge d'erreur proposée pour les pluviomètres Davis est de +-15% et le facteur de correction pour le précis est *2, parce qu'il sous-estime systématiquement le volume vrai.

La connaissance des autochtones a été intégrée dans cette thèse à travers des enquêtes sur la perception de la pluie par les villageois de Tambarga. Les aspects les plus importants pour eux sont la quantité de pluie, la régularité de la pluie et du vent qui l'accompagne parfois. Les conditions qui sont favorables au développment d'un orage ont été étudiées à l'aide d'une analyse en composantes principales (ACP). L'analyse a montré que très peu des événements étudiés sont influencés significativement par les variables étudiées (humidité du sol, pluie précédente, flux de chaleur latente et sensible). La persistence de la distribution spatiale des pluies a fait l'objet d'une analyse. Pour le mois d'août une certaine persistence a été revelée. Durant ce mois les événements de pluie se suivent étroitément.

Finalement, la validité de la formule pour estimer le temps entre le moment où la pluie commence et où il y a une réponse de débit dans la rivière en utilisant de données d'infiltrométrie. La formule est valide pour le bassin versant considéré seulement

si un régime permanent de la rivière est observé (qui ne dépend pas des apports de pluie). Les résultats des analyses presentées dans cette thèse donnent des aperçus différents sur les charactéristiques des pluies. Quelques information peuvent déjà être utilisées, mais afin d'obtenir des résultats plus parlants, les analyses devraient êtres poursuivies sur une période plus longue.

Acknowledgements

I would like to thank Prof. Marc Parlange for the inputs he gave me during the semester. Also I'd like to thank Natalie Ceperley and Theophile Mande for their advice. In Tambarga, the assistants Dramane and Yao Desiré Kouakou provided fundamental technical support to this project.

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1 Context

Rainfall variability

The Sahel is a semi-arid region situated between the Sahara Desert and the humid equatorial Africa. [1] There was a longer period of recurrent droughts in the 1970's and the 1980's. The situation improved in recent years, yet less rain has fallen compared to the amount that was measured before the drought in the 1960's. The rainfall in this region is mostly of convective origin (N. D'Amato, T. Lebel). The rainfall is influenced by the migration of the inter-tropical convergence zone (ITCZ).[2]

In the Sahel region the variability of rainfall is considerable. The variability is observed in space and in time. The erratic rainfall defined by spatial-temporal variability, is explained by irregular movements of the convective systems. For instance, the intertropical convergence zone (definition in section 2) may suddenly move back southwards even if the rainy season is well established. Additionally, the irregularity of the convective systems themselves induces rainfall variability. Local convection triggered by spatial surface heterogeneities, particularly in terms of soil moisture and temperature; create local differences in rainfall as well. The variability of rainfall can be observed at different time scales for example from daily, to seasonal and yearly scales.

The rainfall variability is a characteristic of West Africa. Especially the inter-annual variability is very high. The variability defines the vegetation that grows in this region. The vegetation is specific to this region because of its capacity to adapt to varying conditions. Also the rural communities have shown that they are able to adapt to changing conditions. The rainfall has a large impact on their livelihood, as more than 80% of the population in Westafrica[3] is rural and the agriculture is mainly rainfed. They select also the crop which is mostly adapted to erratic rainfall (e.g. millet).

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[1] P. S. Lucio. « A study on the west Sahel rainfall variability: The role of the intertropical convergence zone (ITCZ) ». *AFRICAN JOURNAL OF AGRICULTURAL RESEEARCH* 7, n°. 14 (avril 12, 2012). http://www.academicjournals.org/AJAR/abstracts/abstracts/abstract2012/12%20Apr/Lucio%20et%20al.htm.

2 John C. H. Chiang. (2002) Deconstructing Atlantic Intertropical Convergence Zone variability: Influence of the local cross-equatorial sea surface temperature gradient and remote forcing from the eastern equatorial Pacific. Journal of Geophysical Research 107:d1, 4004

[3] Ben Mohamed, A., N. van Duivenbooden, et S. Abdoussallam. « Impact of Climate Change on Agricultural Production in the Sahel – Part 1. Methodological Approach and Case Study for Millet in Niger ». *Climatic Change* 54, n° 3 (2002): 327-348.

The intertropical convergence zone

The ITCZ is a zone of convection near the equator and is associated with maximal surface heating due to the sun which is situated directly above. The radiation of the sun and the humidity heats the air. Hence the humidity of the air is increased and it becomes buoyant. Southeast and Northeast trade winds come together and enhance the upward movement of convection. The humid air is raised up following the circulation of the Hadley cell. The air expands and cools down, a process which leads to condensation and cloud formation. Therefore, on satellite images, the ITCZ can be identified as a band of clouds. The convective clouds form a line and are thus part of the westward circulation. Given the energy involved, the events associated with this phenomenon are most often thunderstorms.

As the sun's position relative to the Earth changes, so does the ITCZ. As a result of the meridional displacement of the ITCZ, the equatorial regions experience two rainy seasons and the regions further North or South experience one distinct rainy season. The Sahel corresponds to the latter case. Even further north of the Sahel, rainfall is hindered by the subsidence of dry air, which is at the origin of the Sahara desert. Lucio et al.(2012) decomposed the year into three periods following different precipitation regimes. The dry season was associated with the period from November to May, the rainy season from July to September and the two transition months; June and October. During the wet season the ITCZ migrates North and during the dry season it migrates southwards. The core of the rainy season coincides with the time period when the ITCZ reaches its most northern position.

The band of precipitation associated with the ITCZ is mainly observed over the oceans and extends further to the continents, as it is the case in West Africa. However, convective events can also be initiated on the land surface. The local convection is a process which is controlled by boundary layer characteristics rather than by atmospheric synoptic scales. The process is very complex because of the interactions between different factors such as the surface, the boundary layer, the cloud microphysics and radiation. Therefore, different spatial and time scales are involved. The diurnal cycle of radiation has a large influence on the formation of deep convection. Other important variables are humidification of the free troposphere, the lapse rate of the atmosphere and boundary layer heterogeneities. In particular, soil moisture seems to play an important role in the initiation of convection. The reason is that in the Sahel, generally low latent heat fluxes and relatively higher sensible heat fluxes occur.[4]

The effect of rainfall variability on livelihood

The study area is located in a catchment of the Singou River in the Gourma region of Burkina Faso. The people who live in the village next to the river (in Tambarga) are essentially dependent on farming. Thus the amount of rain that falls has a huge impact on their livelihood. The strong spatial and temporal variability of rainfall requires considerable adaptation. Farmers have to adapt their strategies to the rainfall regime. Graef et al. (2001)[5] cited the erratic rainfall as being the most limiting crop growth factor.

In the Sahelian zone of Niger farmer's strategies to adapt to rainfall variability included exchange of information on rainfall, dry seeding or adapting the planting techniques.[6] This is similar to what we expect in Burkina Faso, where we have a similar climate and livelihood. The different adaption strategies are here considered in further detail.

Specific information regarding rainfall is crucial for farmers. Hence, farmers observe the sky and monitored the soil moisture on the fields. Discussions with other farmers whith their fields further away showed that even at a low scale of only a few kilometers, the rainfall varied considerably. Another strategy is to plant a part of the field when it is still dry (e.g. dry seeding), with the risks that if the dry period lasts too long they lose their entire sowing. High temperatures can also spoil the seeds. In the contrary case, the farmers wait until the beginning of the rainy season. The soil can be examined to verify if the soil moisture is enough to plant. However, there is still a risk that the planting will be lost if a longer dry period follows. Another way to adapt to spatial variability is to plant at different dispersed places and cover as much area as possible. One negative consequence of this strategy is that, if the fields are far from each other, they cannot be sown all at the same time. The fourth strategy is to manage to increase soil fertility using fertilizers or other inputs. The strategy used depends also on the socio-economic situation of the farmer. It is not always possible to use an appropriate strategy.

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[4] F. Couvreux, C. Rio, F. Guichard, M. Lothon, G. Canut, D. Bouniol, A. Gounou, 2011 : Initiation of daytime local convection in a semi-arid region analyzed with high-resolution simulations and AMMA observations. Quart. J. Roy. Meteor. Soc. doi : 10.1002/qj.903

[5] Graef, F., et J. Haigis. « Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies ». *Journal of Arid Environments* 48, nº. 2 (juin 2001): 221-231.

[6] Graef, F., et J. Haigis. « Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies ». *Journal of Arid Environments* 48, nº. 2 (juin 2001): 221-231.

In addition, the problems related with rainfall variability are not only the possibility of low rainfall over a longer time period, but also rain events with high intensity can occur which have negative consequences. If the rainfall rate is relatively high, a crust forms on the surface of sandy soils, such that the infiltration rate is reduced and a higher fraction of the water is lost as surface runoff. In general, the problems the farmers are facing in the Sahelian zone are not exclusively due to climatic factors. The effects of both, climate change and land cover change induced by the intensification of agriculture, contribute to desertification (Sahelisation). It is difficult to distinguish which effect is provoked by which cause and synergetic effects are observed as well. Regarding precipitation, this phenomenon translates a latitudinal shift of the isohyets in direction of the South. Thus, the overall rainfall is reduced.

Problem solution

In the catchment of the Singou River 13 sensorscope stations were installed, which continuously monitor various meteorological parameters at a 5 minutes time step (2010). The Sensorscope networks are wireless sensor networks which are particularly adapted to record spatio-temporal data over a long time period (environmental monitoring). The map below is showing the location of the different stations in the watershed. Three stations (1009, 1010 and 1014) were installed on the hill. All the other stations are at different locations in the valley. The stations 1001 and 1008 are near by the outlet of the river.

The advantages of the sensor cope stations are that they are flexible (suitable for various environments) and relatively cheaper sensing stations.[7] The solar panel ensures that the necessary energy is supplied to record the data. This is an advantage for the usage of such stations in a zone where the sun is almost in zenith position. The sensors measure air humidiy and temperature, rain, soil moisture, solar radiation, wind direction and wind speed. One of the problems of the stations is, that the electronics must be protected against dust and humidity. The humidity can cause damages such as a court-circuit of the connector or corrosion of the connector. Another drawback is that communication problems may occur.

The photo shows the station installed next to the village:

[7] François Ingelrest , Guillermo Barrenetxea , Gunnar Schaefer , Martin Vetterli , Olivier Couach , Marc Parlange, SensorScope: Application-specific sensor network for environmental monitoring, ACM Transactions on Sensor Networks (TOSN), v.6 n.2, p.1-32, February 2010

Figure 1 Sensorscope station

Site description

The Singou river catchment is located in the Gourma region in the SouthEast of Burkina Faso. The Singou River catchment is formed by the Gobnangou chain which is a sandformation of maximal altitude of 365 m.a.s. [8]

The majority land is cultivated with millet and corn. The farmers also plant cotton, rize or sorghum. The agriculture is essentially rainfed. The landscape resembles a typical south soudaninan Savannah. In the village of Tambarga, families live together in circularly arranged buildings.

The climate is variable. The daily maximum temperatures vary between 30 and 46° C for the year 2010. The precipitation follows a seasonal cycle, with a rainy season from May to October. Also the temperature is affected by seasonality. The yearly maximum temperature is observed in April and its value decreases slowly during the rainy season.

[8] M. Parkan, Land Cover and Land Use Change in Tambarga (2009-2011),Burkina Faso, SIE Project, Autumn 2011

Objectives

The objective of this Master's project is to analyze the variability of rainfall in the Singou river catchment using the rain gauge data measured by the sensorscope stations. The period considered here is May to August 2010.

In the first section, the differences in measurements between the different stations induced by errors are evaluated. The errors can represent instrumental errors or communication errors. The purpose of this error estimation is to correct the data in order to comprehend the real variability of the rain measurement. Errors induced by external factors, such as wind or an animal passing, are difficult to estimate and were not considered.

In the second section, the rainfall in Tambarga is briefly described. The rain events are identified according to certain criteria and the period considered is defined. In this part the behavior of the rain gauges is examined, and the stations which do not provide reliable data throughout the period of interest, are excluded.

In addition to scientific knowledge, this thesis will examine indigenous knowledge of rainfall. A survey was conducted in Tambarga with the goal to investigate the perception of rain by the villagers. This is presented in the third section. Open questioning allowed understanding their point of view and identifying the aspects of rain which are important. Another goal was to link the results of the survey with the other analysis in the subsequent sections. As the people in Tambarga are always at the field of study, they have a certain knowledge which a scientist cannot have. The time of observation by scientists is limited whereas indigenous knowledge developed over a considerably larger time scale.

The principal components analysis (PCA) is used to evaluate the influence of certain parameters in the appearance of rain events. The aim is to see if certain conditions favor rain events. Additionally, similar rain events can be regrouped and then compared to the results of other analysis. The PCA is presented in section 4.

The rainfall variability in time is part of the analysis of persistence. The persistence analysis focusses on the differences between the measurements of the rain gauges at a given event and their relation to differences in the subsequent event. If there is a correlation between these differences, it can be concluded that a certain distribution pattern of rainfall persist. If there is no correlation, the pattern also varies in time. If there is certain persistence, the rainfall could be predicted, which may help the farmers in their decisions.

Not only does the rain influence the distribution of water in the catchment, but also the soil moisture and, in particular, the soils infiltration capacity. Infiltration experiments were carried out in February 2012 at certain stations. This information allows determining the fraction of rainfall which infiltrates and contributes to soil moisture and groundwater. Also the time until the water ponds on the surface can be determined, knowing the infiltration capacity and the rainfall intensity. It is interesting to see if the formula is applicable to this data.

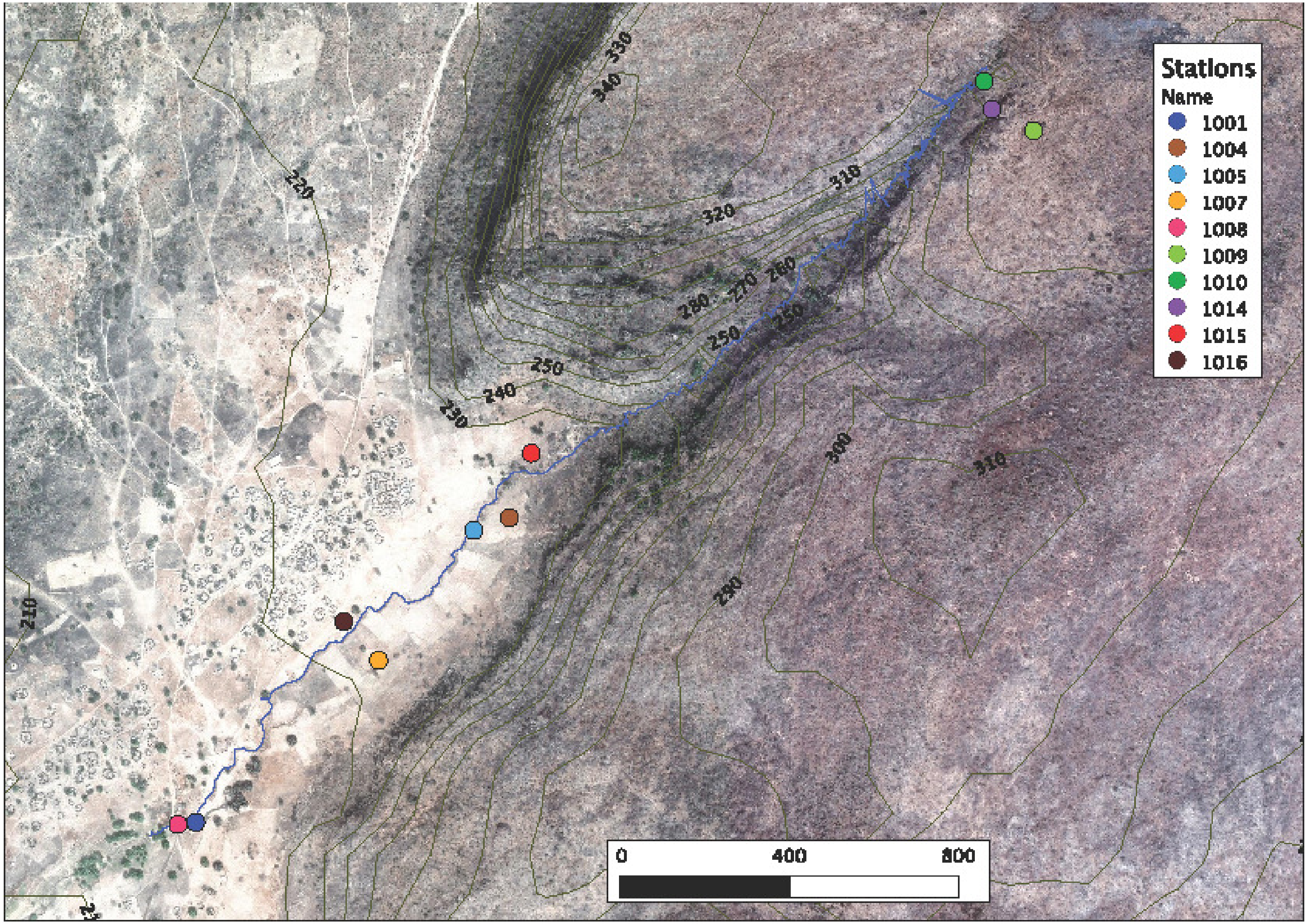


Figure 2- Map of the catchment with the locations of the sensorscope stations

2 Experiments

The accuracy of two types of rain gauges was evaluated: the précis rain gauge and the Davis rain gauge. Rainfall measurements are important in Climatology and Hydrology. Although, the advances in remote sensing are considerable, rain gauges need still to be used for calibration.

2.1 Description of the rain gauges

2.1.1 The Davis Rain Collector

The Davis rain gauge is used together with the sensorscope stations. At each station one such rain gauge is installed (in 2010). The functioning is as follows. The water is caught by the cone and is directed to through the funnel where it drops into the upper bucket of the two buckets which are balanced on the pivot. The top bucket is filled with water till the calibrated volume is reached and it goes down and tips. The water empties through the drain screens. When it tips, a sensor (reed switch) is triggered. This tip is recorded at the weather station (sensorscope). The calibrated rain height per tip is 0.254 mm. The magnet ensures that the position is held till the calibrated volume is reached.

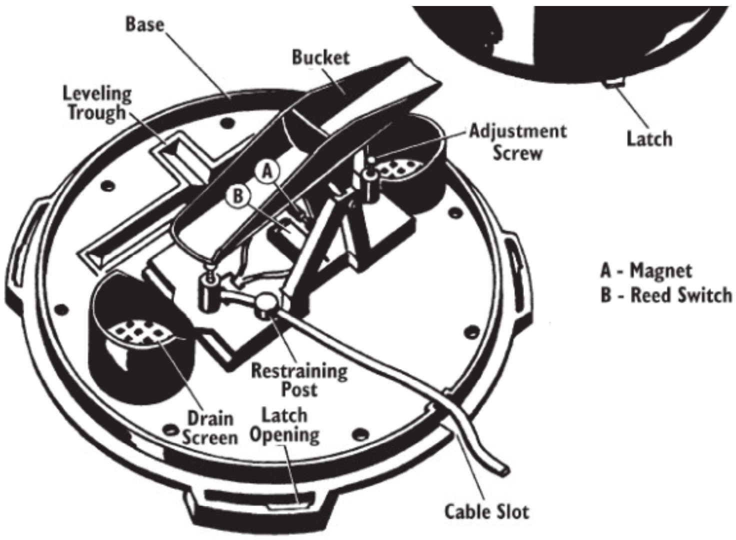


Figure 3 Internal components of the rain collector[9]

[9] Davis Instruments Corporation, «Rain Collector II».Rev B Manual (10/21/05) 2004

The accuracy was indicated as follows:

+-4%,+-1 count between 0.2 mm and 50 mm per hour

+-5%,+-1 rainfall count between 50 and 100 mm per hour

2.1.2 The précis rain gauge[10]

The functioning is similar to the one of the Davis rain gauge. The tipping of the bucket induces the interruption of an electric durrent. The calibration height is smaller than for Davis; it is only 0.1 mm. If an intensity of 400 m/h is exceeded the rain gauge is saturated and the intensity measurements are wrong. However the measurements of the volume of rain remain correct. The accuracy of measurements at low intensity is about + or – 4% according to Meteo France. For higher intensities (>150 mm/h) the error grows to -10% (underestimation).

2.2 Sources of errors in measurements

The error can be caused by the wetting of the cone. The water remaining there is not measured. Other Errors which cannot be detected by the experiments, and may occur occasionally are the malfunctioning of the rain gauge due to overfill, bad movement of pivot or bad temporal resolution.

The errors due to the instrument is not the solely cause, that the measurements are not accurate. Meteorological factors such as temperature, evaporation and wind may also induce some errors. “The covers of the data loggers sometimes crack in the sun heat and condensation can cause short-circuits.” Especially wind can have a large effect on the amount of rain caught by the collector. The rain gauge is an obstacle in the wind field which gets distorted. The wind accelerates at the orifice and eddies are formed in proximity. The errors grow with wind speed as well as rain intensity. Also the higher above the ground the rain gauge is fixed, the larger the difference between measured and actual rainfall height becomes.

[10] Mylène Civiate et Flavie Mandel - ENM, « la mesure de la hauteur des précipitations ».- Version 1.0-décembre 2008

However, raindrop splash can also falsify the measurements. Its effect can be reduced if the rain gauges are fixed at a certain distance above the ground level.

Other factors from the immediate environment can also affect the quality of data. Debris or dust can accumulate in the collector and hinder the water to flow through the funnel to the tipping bucket. Also insects may enter the bucket and obstruct the funnel. If trees are situated in proximity, the measurements can also be affected by interception. Most often these factors lead to underestimation of the rain. They can be avoided, if the rain gauges are visited and verified regularly, as it is the case in Tambarga. An assistant is visiting the sensorscope stations on a daily basis.

The sampling errors of tipping-bucket rain gauge measurements were investigated by Habib et al. [11] They focused on the small-scale rainfall variability. To verify the measurements of the tipping-bucket rain gauge, an optical rain gauge was employed which yields ultra-high-resolution measurements. Their evaluation was based on rain rates and the temporal as well as the volume resolution were considered. Significant errors were found for 1-min estimates and low rain intensities. For larger time scales (15 min), the error is neglectable. In their recommendations, they propose sampling intervals of about 5-10s and a bucket size which should not exceed 0.254 mm. The error was reduced significantly when the bucket size was decreased from 0.254 mm to 0.1 mm.

2.3 Introduction to experiments

The experiments presented here are the continuation of experiments conducted in a previous project. In the previous project, experiments had been carried out with the objective to estimate the accuracy of the rain gauges (Davis and précis). The set up consisted of pouring a known volume of water into the rain gauge and compare the measured volume to the actual volume of water added. The results of the experiments concerning the Davis rain gauges, suggested that the true volume was always underestimated by about 30%. As for the précis

[11] Habib, Emad, Witold F. Krajewski, et Anton Kruger. « Sampling Errors of Tipping-Bucket Rain Gauge Measurements ». *Journal of Hydrologic Engineering* 6, n° 2 (avril 2001): 159-166.

rain gauge, the underestimation was about 36%. However, only few experiments had been carried out. In order to confirm these results, further experiments have been made recently using the experience acquired from the previous ones. These recent experiments are presented here.

Generally, the objective of the experiments is to evaluate the instrumental error. If a systematic error in the measurements can be detected and estimated, a correction factor can be applied to the data. The previous experiments had some limitations. The water was poured at a rather fast rate, which is not necessarily representative of the intensities observed in the catchment of the Singou River.

2.3.1 Experiment in Tambarga (February 2012)

In February 2012, the current rain gauges in Tambarga were tested by adding a volume of 100 ml of water. As the volume of water is known, it can be compared to the measured volume. The following formula was used for the comparison:

$$relative\ difference = \frac{V_{cy} - V_{rg}}{V_{cy}} * 100\%$$

The results are summarized in the table below. Several stations have two rain gauges and the second raingauge is indicated by the letter b. For station 1267, the experiment was carried out two times and the second experiment is indicated by (2). The values of relative difference are always positive, which translates in underestimation of the true volume. The experimental set up resembles to the experiments which had been carried out before. Accordingly, the results are similar. However, the degree of underestimation is generally lower. The most frequent value is around 20 %. Station 1008 had communication problems during the experiment. That is the reason why it did not measure a large part of the added volume.

Table 1- the relative differences for the measurement at each station

station/gauge	underestimation [%]
1006	18.47%
1006b	2.16%
1008	89.19%
1010	2.16%
1014	13.03%
1261	18.47%
1261b	13.03%
1265	18.47%
1265b	23.90%
1266	18.47%
1266b	23.90%
1267	23.90%
1267b	29.34%
1267 (2)	23.90%
1267b (2)	23.90%
1260	18.47%
1260b	18.47%

From this experiment, it may be concluded that there is a systematical error of about 20%. Nevertheless, it is not clear if this error is reflecting the overall accuracy of the measurements made by the rain gauge. The cause of this error may be due to the fact, that the water is added to fast and the rain gauge cannot compute the whole water of volume flowing through it.

2.3.2 Experiment at EPFL (Lausanne) in front of the GR building

The objective of this experiment was to describe the relationship between the estimation error and the volume added. The volume was again poured by hand using a graduated cylinder, but at a lower rate. Most often the volume was added during five minutes. As the volumes are varying, the rate is also different from one addition to the other. The below graph shows the comparison between the height added and the height measured.

The black line is the line of ratio 1:1 which would occur in the ideal case in which the measurements are equal to the true volumes. In the legend the corresponding volumes are listed. On this graph, 26 points representing 26 additions of water should appear. This is actually the case, but in several cases exactly the same volume was measured so that the points are superimposed and aren't visible. In the legend just after the volumes, also the number of points expected on the graph is mentioned.

The general trend observed is still an underestimation of the actual heights. Sometimes the height is overestimated, but the underestimation is far more frequent. In general, the values of relative difference vary considerably and there is no value that may be considered being the most frequent, as it was the case for the experiment in Tambarga. The relationship between the height added and the height measured appears to be linear and no variation with increasing volume is observed.

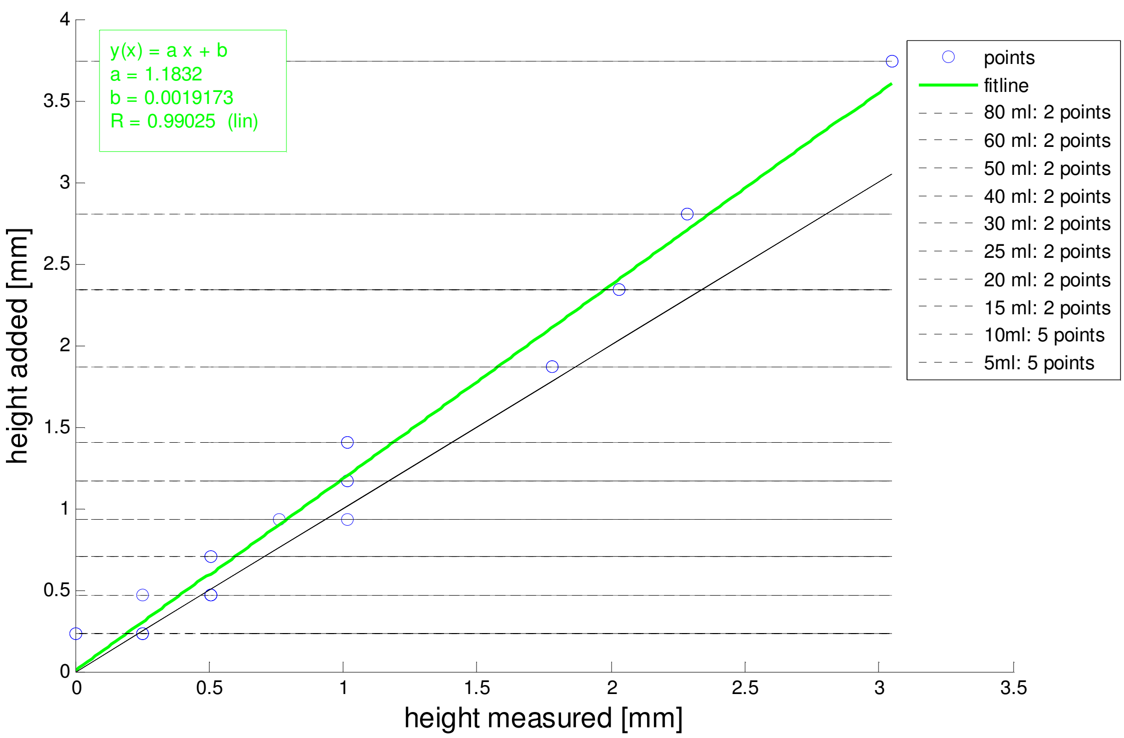


Figure 4- The comparison between the height added and the height measured

The experiment confirms that the volumes are underestimated, but it is not clear to which degree, as the values are varying considerably. If the whole volume is summed up, the underestimation is around 16%, which is slightly better than before. There is also some doubt if the rate was sufficiently low during the experiment, as it was added by hand. In order to get even a more accurate result, in the following experiment a peristaltic pump is used.

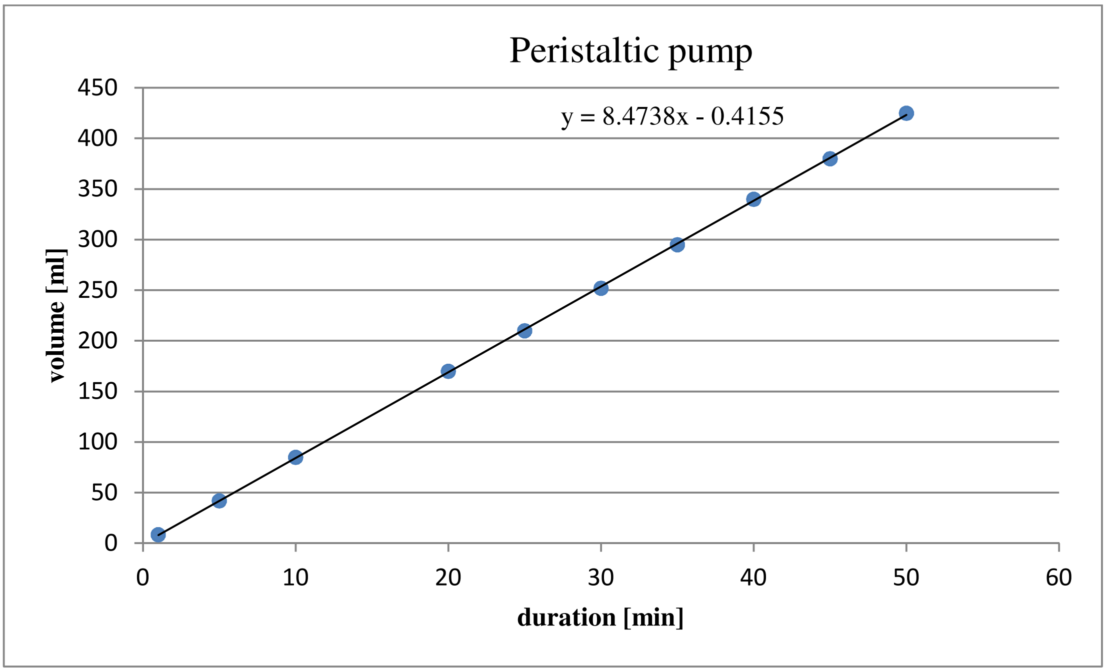
2.4 Experiments using a peristaltic pump

2.4.1 Description ot the peristaltic pump

A peristaltic pump (IPC) from ismatec was used. It is a microprocessor controlled dispensing pump. This pump is appropriate because it is adapted to low flow and a requirement was to obtain lower flow rates as in the previous experiments. Thus, the errors induced by adding the water too rapidly do not need to be considered anymore. The mechanism of the pump is the same as the functioning of the human intestine, which displaces matter as a succession of contraction and relaxation. The tubing is squeezed by means of steel rollers. The pump could be connected to several tubes at the same time. Hence, more than one rain gauge could be tested simultaneously. The flow rate was approximately the same in each tube. However, air bubbles were observed in some tubes, which are due to aspiration of air in the joints. This problem couldn’t be fully eliminated. Therefore, the water coming out of the rain gauges was caught in bucket and measured separately after each run. The corresponding flow rates for each tube were calculated.

2.4.2 Calibration

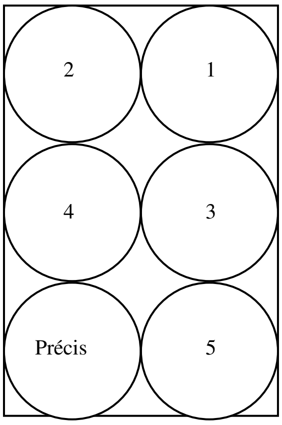
Throughout the experiments the same flow rate was used. At the beginning of each run, the pump was turned on for at least 5 minutes to ensure that all the tubes are completely filled. Before starting the experiments, the peristaltic pump was run for different periods of time and the amount of water pumped was measured. The following calibrated curve was obtained:



As a linear curve is obtained, the flow rate remained constant and the volume only varies with duration. In total, 5 different experiments are presented here.

Part I

. In the first part, the set up was at follows:



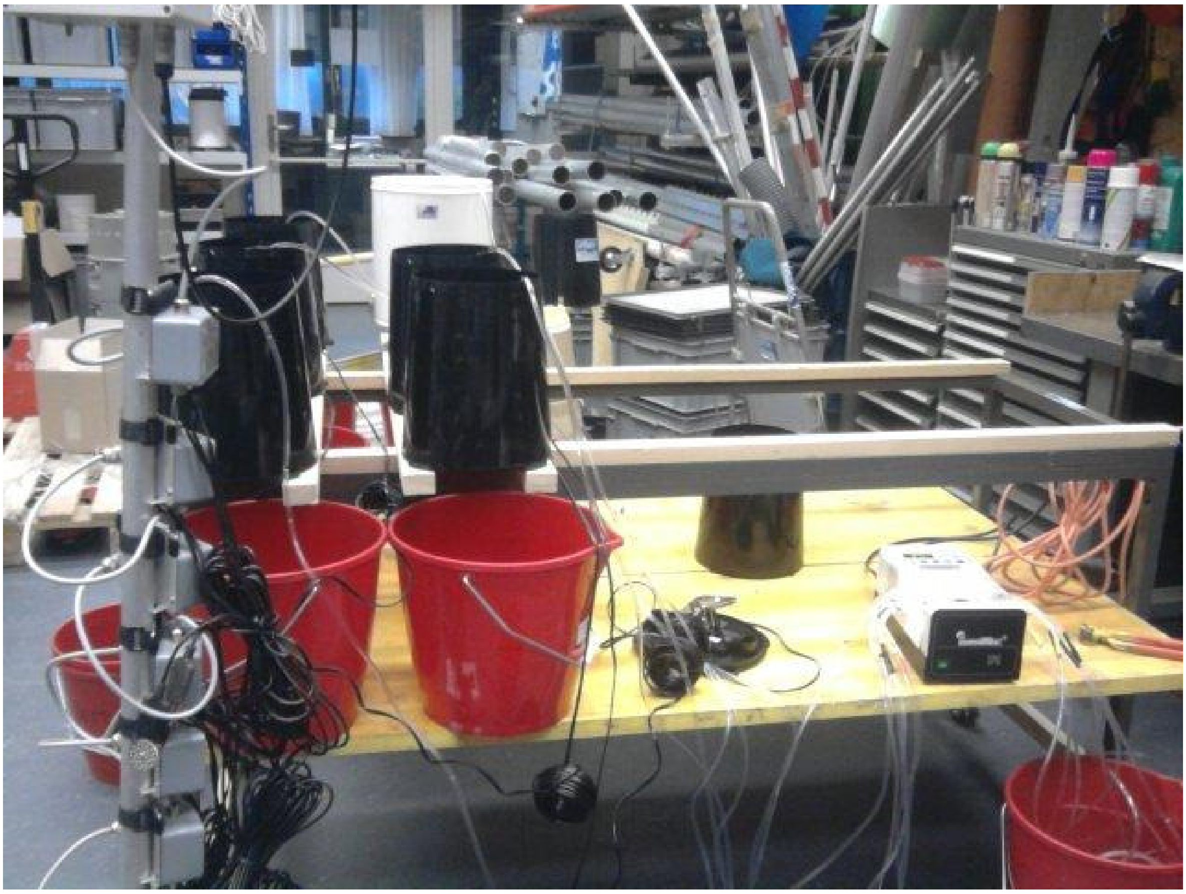


Figure 5- The experimental set up in the laboratory

Taking into account the fact, that depending on the tubes the flow rate may differ slightly, the tubes were rotated after each run. In the first case, the water was added during 5 minutes. In the second case, the water was added during a time period of 30 minutes. The tubes and the rain gauges were both numerated from 1 to 6. After each second addition the tubes were rotated. The rotation was stopped when each tube had been in each rain gauges (e.g. after 6 measurements). Thus, 12 different measurements were carried out (2 times for each arrangement of tubes). In the picture above, the peristaltic pump is shown on the right side and the six rain gauges under which red buckets were put on the left hand side.

A. Experiment 21st May 2012, 5-minutes run

The water in the buckets was poured in a graduated cylinder. The volume measured in the graduated cylinder was compared to the volume of water measured by the rain gauges.

The results are presented in the following figure. The x-axis corresponds to the different tubes and the y-axis shows the height of the water volume measured by dividing by the catchment area of the bucket.

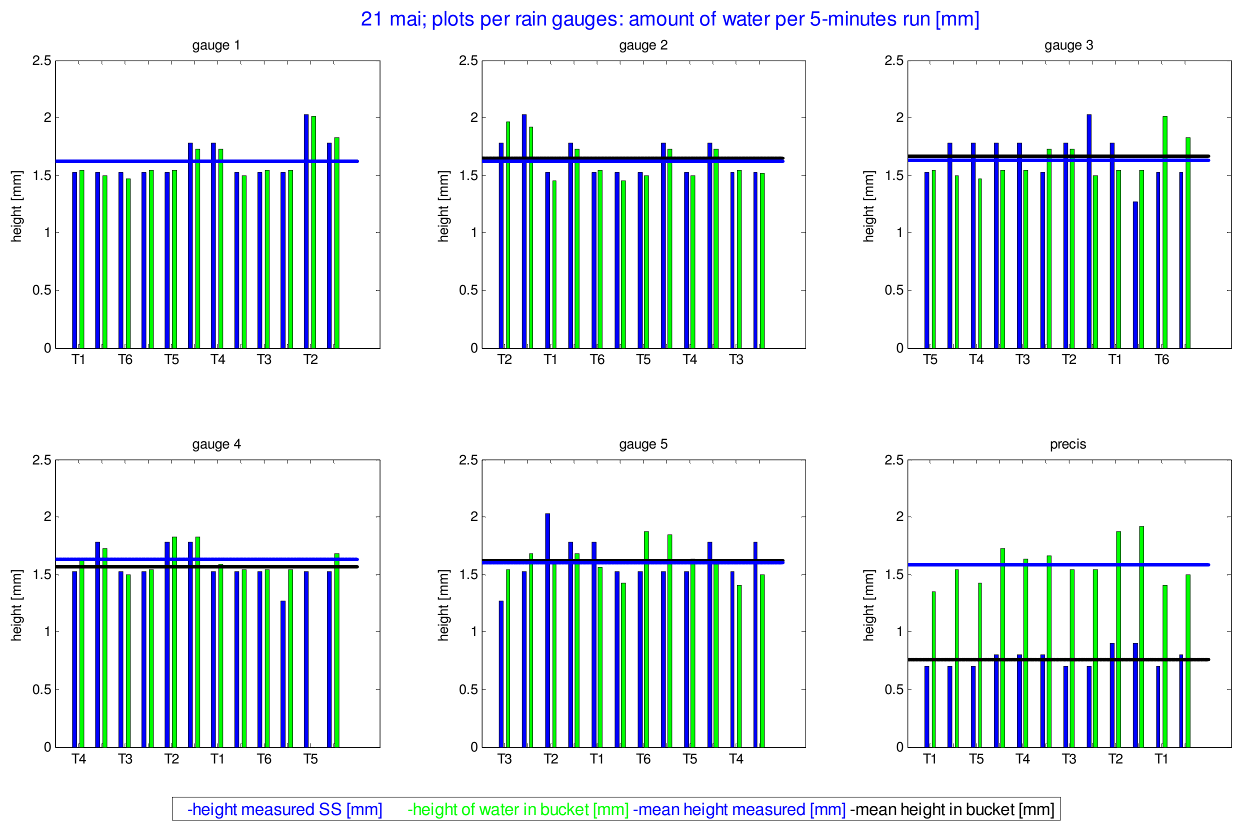


Figure 6- Part I A- Comparison of heights- plots rain gauges (tubes are rotated)

These results were rather surprising. Contrary to an expected underestimation of the water volume measured, the rain gauges most often measured more than what was measured in the graduated cylinder. The measurements of the graduated cylinder were expected to be more accurate. However, they are also be affected by errors. The precision of these measurements depend on the observer's eye as well as the graduation on the cylinder. Furthermore, the wetting of the bucket and the fraction of water that remains inside the latter may explain the lower volumes measured as compared to Davis. This effect may be smaller when considering larger volumes. The second experiment was carried out with 30 minutes pumping time, which results in a volume 6 times bigger than the one in the previous experiment. As already mentioned, differences between the different tubes were observed. To compare the water height per tubes, another plot was made with a graph for each tube. In particular, the précis rain gauge measured considerably less water throughout the experiment. The graph is shown in the appendix.

B. Experiment 22nd May 2012, 30-minutes run

This time the tubes were changed after each run.

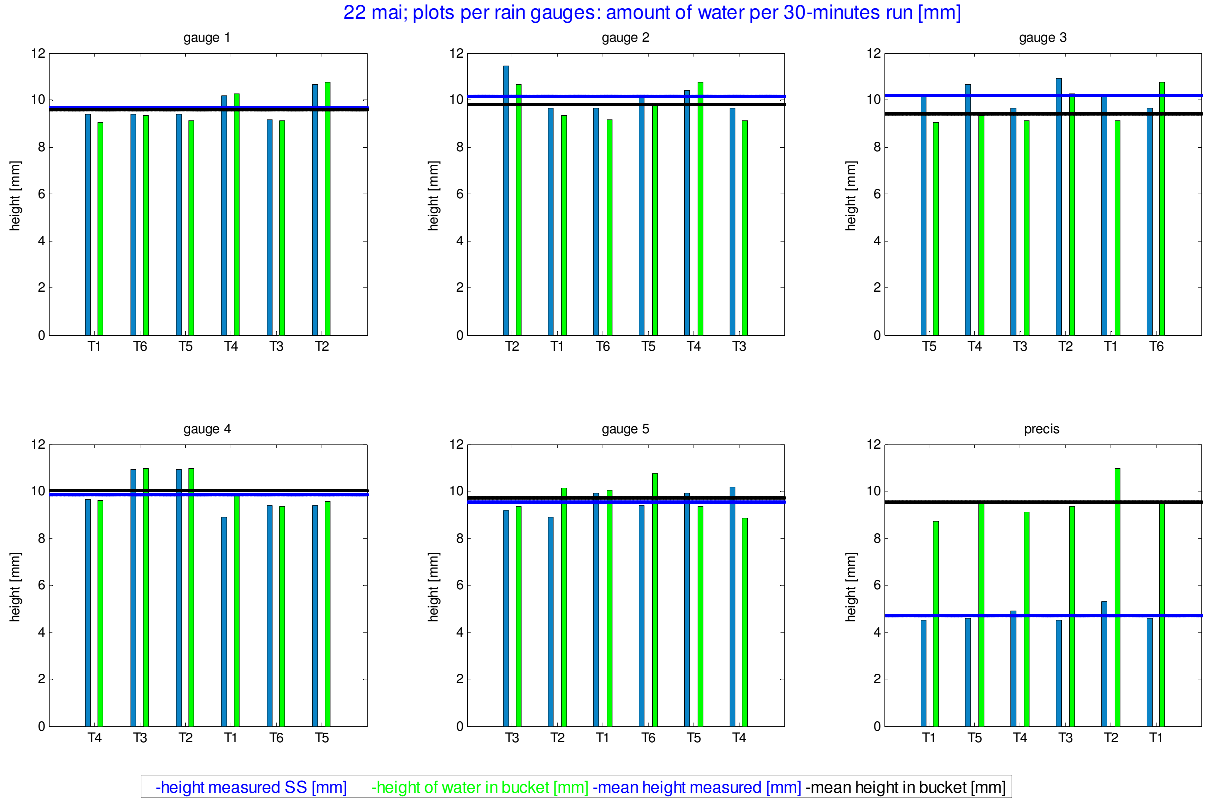


Figure 7- Part I B- Comparisons of heights

The results are comparable to those obtained for a shorter pumping time. Once again the précis rain gauge underestimates always the added quantity of water. In the following table are shown the relative differences of the measured volumes by the rain gauges as compared to the volumes measured with the graduated cylinder. More precisely, the following formula was employed:

$$relative\ difference = \frac{V_{cy} - V_{rg}}{V_{cy}}\ [-]$$

V_{cy}: volume measured by cylinder

V_{rg}: volume measured by rain gauges

Negative values correspond to higher estimates by the rain gauges and positive values to lower estimates in comparison with the volume obtained by the graduated cylinder.

For the first experiment, the values are shown in the following table for each run (columns) and rain gauge (rows).

Table 2

A. 21st May- 5 minutes run													min	max
1	1.17%	-1.92%	-3.54%	1.17%	1.17%	-2.84%	-2.84%	-1.92%	1.17%	1.17%	-1.13%	2.44%	-3.54%	2.44%
2	9.41%	-6.06%	-5.21%	-2.84%	1.17%	-5.21%	-1.92%	-2.84%	-1.92%	-2.84%	1.17%	-0.35%	-6.06%	9.41%
3	1.17%	-5.69%	-11.91%	-5.69%	-13.58%	-6.93%	4.88%	-10.09%	-8.71%	20.06%	-8.71%	-1.92%	-13.58%	20.06%
4	6.82%	-2.84%	-1.92%	1.17%	2.44%	2.44%	4.08%	1.17%	1.17%	17.64%		9.41%	-2.84%	17.64%
5		-5.21%	-8.71%	7.20%	-5.69%	1.17%	-3.54%	4.08%	1.17%	-0.13%	-5.21%	-2.84%	-8.71%	7.20%
P	48.34%	54.61%	50.89%	53.73%	51.09%	51.77%	54.61%	54.61%	51.85%	53.02%	50.07%	46.50%	46.50%	54.61%

The red color corresponds to negative values. The pure blue color corresponds to small positive values and the green color corresponds to large positive values. As for to the Davis rain gauges, the relative differences vary considerably with the lowest value of -13.58 % and the highest value of 20 %. It seems that the rain gauge number 3 represents higher values for measured volumes than expected. By contrast, the précis underestimates the volumes. The two gaps in the table is missing data. In order to get an overall estimation of the relative differences, the average value was calculated as presented in the first column of the table below. The second column shows the average value of all the positive values and the third column the average of the negative values. Only, rain gauge 4 presents an overall average value which may indicate underestimation. The average value is possibly not an adapted measure to compare the performance of the different rain gauges, because the volumes of water involved vary from one tube to the other and in time.

Table 3

mean	mean +	mean -
-0.49%	1.38%	-2.36%
-1.45%	3.92%	-3.24%
-3.93%	8.70%	-8.14%
3.78%	3.40%	-0.77%
-1.61%	3.40%	-4.47%
51.76%	51.76%	-

In the end the total volume of water pumped during the experiment was calculated and compared to the total volume measured. As a general rule, the Davis rain gauges tend to overestimate the expected values of volume of water.

Table 4- comparing total volumes

rain gauge	1	2	3	4	5	précis
difference total volume[ml]:	-2.0412	-5.4768	-15.9124	-18.2344	-33.0412	212.12
relative difference total volume[%]:	-0.49%	-1.31%	-3.85%	-4.75%	-8.57%	51.86%

The table shown below concerns the second part of the experiment. The values of the relative difference are shown for the six runs and all the rain gauges.

Table 5- relative differences

B. 22st May- 30 minutes run

							min	max
1	-4.21%	-0.56%	-3.14%	1.17%	-0.35%	0.74%	-4.21%	1.17%
2	-7.28%	-3.28%	-5.38%	-3.54%	3.10%	-5.92%	-7.28%	3.10%
3	-8.71%	-5.21%	3.93%	-1.62%	-8.71%	-8.71%	-8.71%	3.93%
4	-0.27%	0.54%	0.54%	9.41%	-0.56%	1.89%	-0.56%	9.41%
5	-2.99%	2.44%	-4.43%	-0.56%	-3.41%	-1.13%	-4.43%	2.44%
precis	48.50%	51.98%	46.23%	51.85%	51.74%	51.98%	46.23%	51.98%

The norm of the values is smaller, when considering both negative values and positive values in the table. The larger volumes may explain the diminution of the error.

Table 6- Comparison of total volumes

	1	2	3	4	5	précis
difference total volume[ml]:	-11.7524	-45.544	-57.9796	24.5052	-20.4456	619.24
relative difference total volume [%]:	-0.95%	-3.62%	-4.63%	1.90%	-1.69%	50.47%

Regarding the total volume of the experiment, the relative differences are very low in the case of the Davis rain gauges. It is not clear if these errors are due to the wetting of the bucket.

Part II

In the second part of the experiment, only 2 rain gauges and the précis rain gauge were tested. The pumping time chosen was 5 minutes. The purpose of this experiment was to repeat the experiment above and compare the results.

A. 22st and 23rd May- 5 minutes run

The cumulative height per run is shown in the graph below. The tubes were rotated after each run. The x-labels correspond to the numbering of the tube. In the end all tubes were bound together put in each rain gauge successively. The forth bar on each graph represents this case. Rain gauge 1 computes always a height which is higher than the one measured in the bucket. The same applies for rain gauge 2, except in the third run. As before, large differences were observed considering the précis rain gauge, which seems to measure substantially less. By contrast, the Davis rain gauges have smaller differences and it is necessary to verify what the origin of those is.

In the table below is presented the relative difference for the 2 rain gauges and the 4 runs.

Table 7-relative differences

II A 22st and 23rd May- 5 minutes run				
1	-13.24%	-109.06%	-1.92%	-6.06%
2	-15.65%	-99.31%	50.59%	-49.48%
precis	42.93%	6.62%	68.30%	41.15%

The values are unexpectedly high in the second run. This experiment did not confirm the results above, neither contradicts them. As a consequence, the overall accuracy of the total measured volume in the experiment is very low. The norm of all relative difference is larger than 30 %.

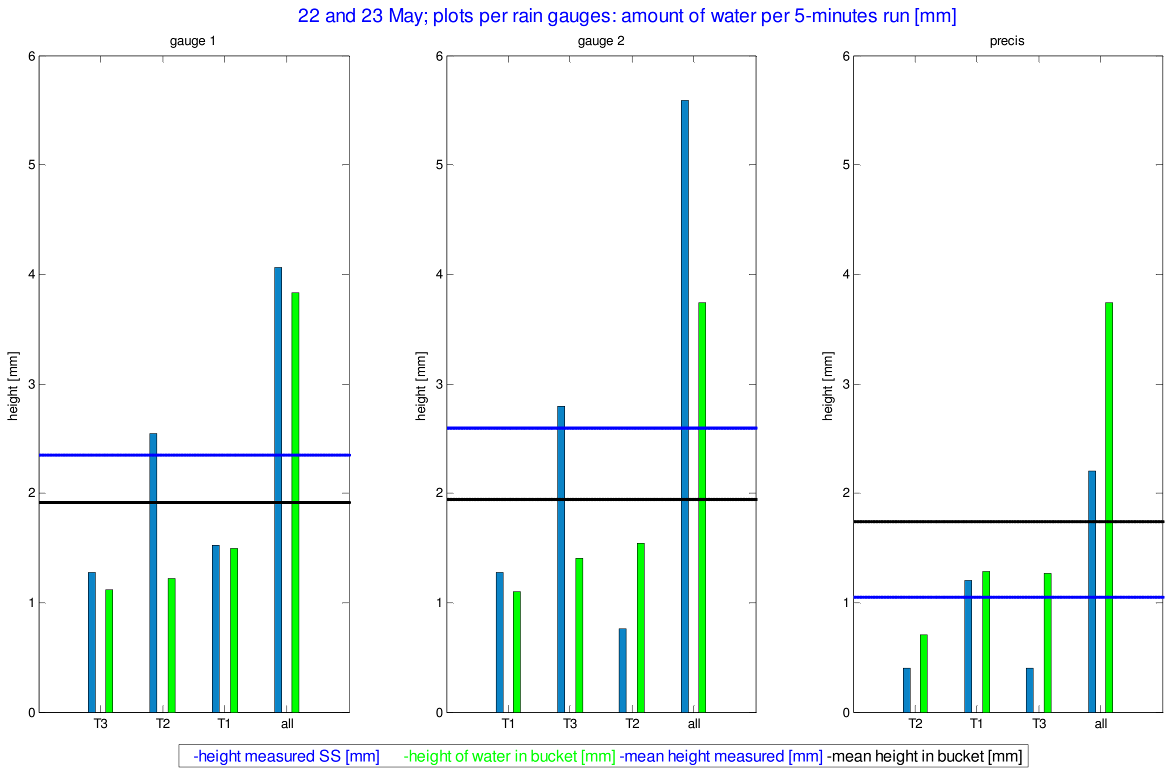


Figure 8-Comparison of height measured to the height in the bucket

B. 23rd May 2012- 30 minutes run

The experiment was also repeated for a pumping time of 30 minutes.

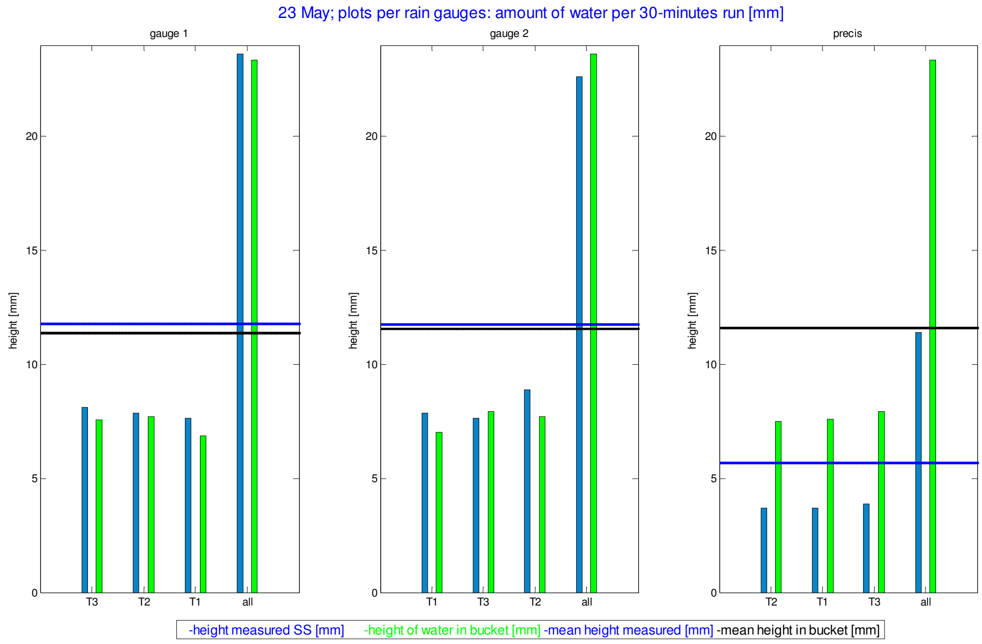


Figure 9-Comparions of height measured to the corresponding height in the bucket

As shown in table 8, the relative differences are in the same range as above. It can be concluded, that the rain gauges generally measure a larger volume of water and the précis rain gauge considerably less than what is read from the graduated cylinder.

Table 8-relative differences

II B 23rd May- 30 minutes run

1	-7.37%	-2.12%	-10.93%	-1.10%
2	-12.34%	4.08%	-15.30%	4.20%
precis	50.51%	51.42%	50.91%	51.21%

As already mentioned above, the precision of the measurements are insufficient. In particular, the precision of the measurement of the "true volume" needs to be increased. Therefore, in the third part of these series of experiment, a scale was used to estimate the volume of water.

Part III

In this part of the experiment, the buckets were weighted after each run and the weight of the empty bucket was subtracted from the total weight. The weight of water is converted in volume assuming a density of 1'000 kg/m^3.

A. 4th of June- 10 minutes run

On the graphs below are shown the volumes per 10-minutes run for 2 Davis rain gauges and the précis rain gauge. The blue bars depict the volume measured by the rain gauges and the green bar the volumes calculated from the weight of water obtained by the scale.

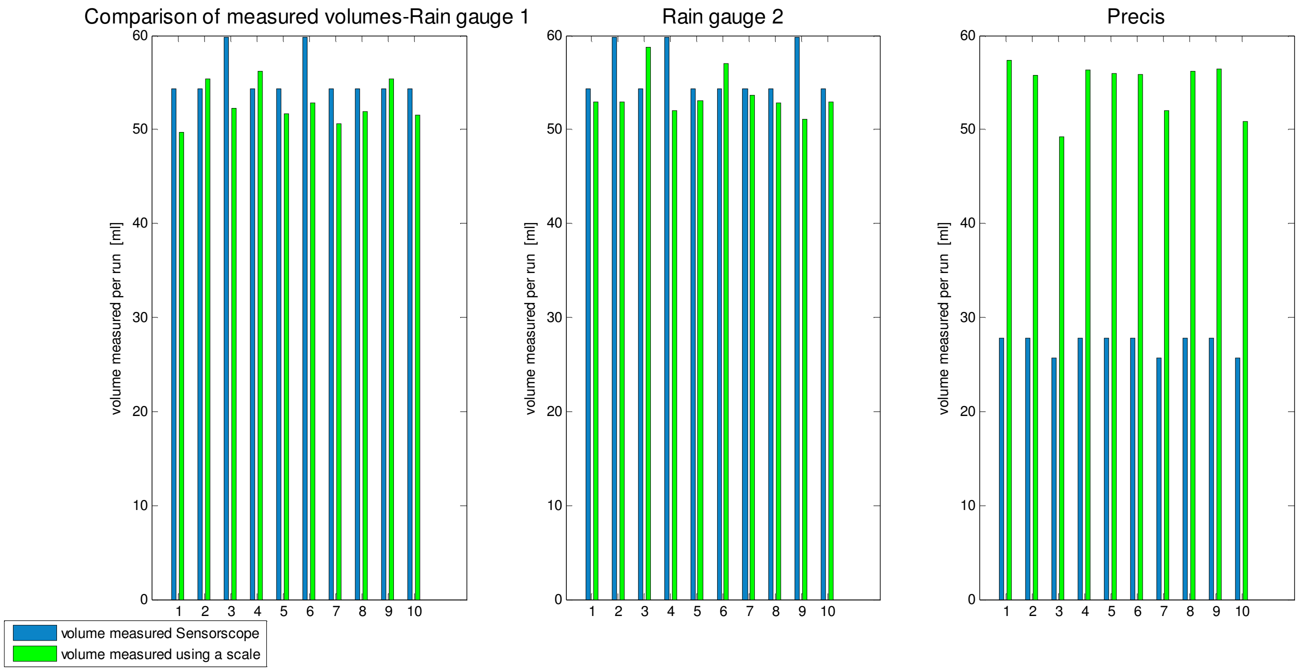


Figure 10-Comparison of measured volume to the volume determined by the scale

The three graphs resemble to the graphs of the previous experiments, with lower differences of the Davis rain gauges and higher differences for the précis rain gauge. It is clear that the précis underestimates the actual volume. In the table below are shown the values of the relative difference. It is remarkable that the degree of underestimation by the précis rain gauge is quasi constant and of about 50 %. By contrast, the other two rain gauges most often overestimate the true volume (negative values of relative difference) and the degree by which they overestimates varies significantly. However, sometimes the measured volume is very close to the "true volume". It is important to mention that the true volume considered here is still influenced by the accuracy of the scale and the density which varies with temperature and pressure, two parameters which weren't kept constant throughout the experiment.

Table 9-relative differences

II A 4th June- 10 minutes run

											min	max
1	-9.41%	1.80%	-14.46%	3.37%	-5.20%	-13.24%	-7.44%	-4.71%	1.97%	-5.34%	-14.46%	3.37%
2	-2.75%	-12.92%	7.46%	-14.90%	-2.42%	4.67%	-1.41%	-2.93%	-17.08%	-2.58%	-17.08%	7.46%
precis	51.55%	50.14%	47.82%	50.62%	50.34%	50.21%	50.59%	50.52%	50.72%	49.46%	47.82%	51.55%

Thus, for the précis rain gauge a systematic error can be defined. This is not the case for the other rain gauges. Nevertheless an error range could be specified.

Here we only consider one fixed pumping time. In the following experiment, the time was changed so as to examine if the different volumes have an effect on the accuracy of the measurements. The pumping rate was held constant.

II B 11th June- varying pumping times

One single Davis rain gauge and the précis rain gauge were tested. The pumping time was increased at each run by 5 minutes, from 5 till 40 minutes.

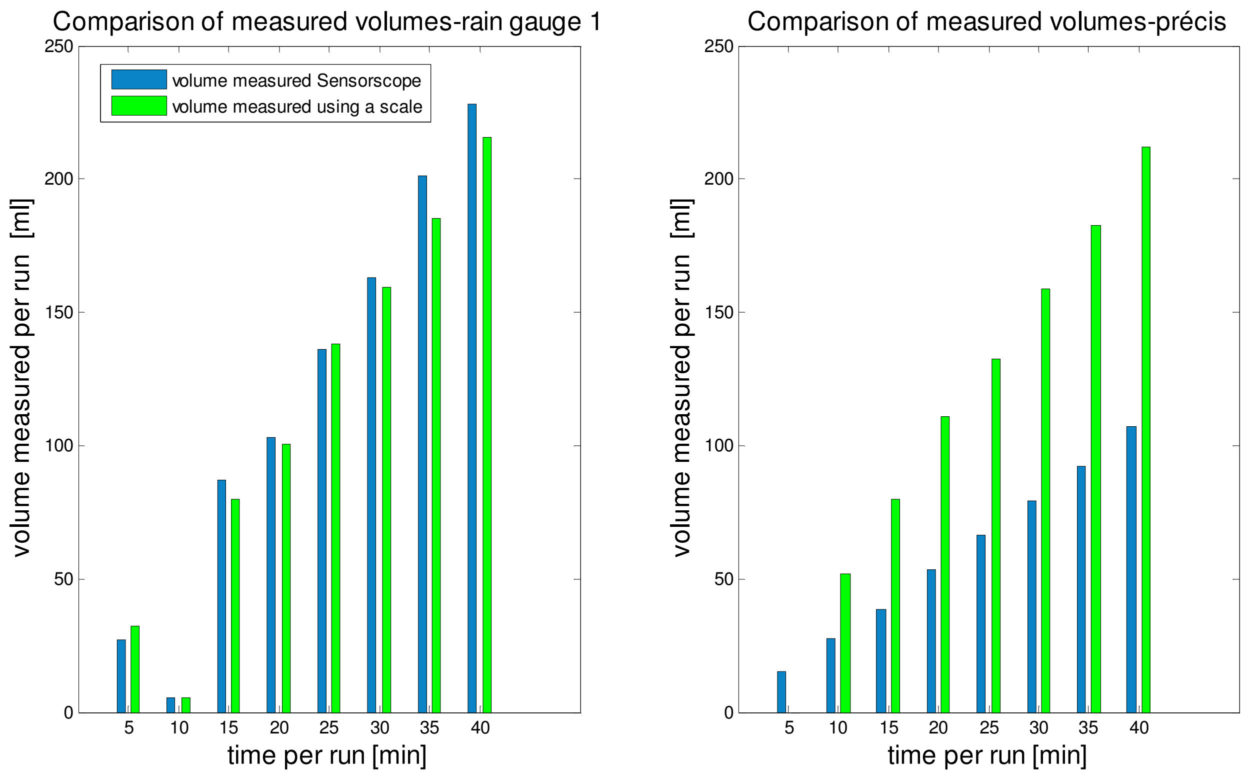


Figure 11-Comparison of measured volume to the volume determined by the scale

The Davis rain gauges still measured more than the scale independently of the volume. The underestimation of the précis rain gauge seems to be proportional to the volume of water added. As the volumes are varied, a linear curve can be fitted on the scatterplot of the "true volume" vs. the volume measured. The corresponding graphs are shown in the figure below.

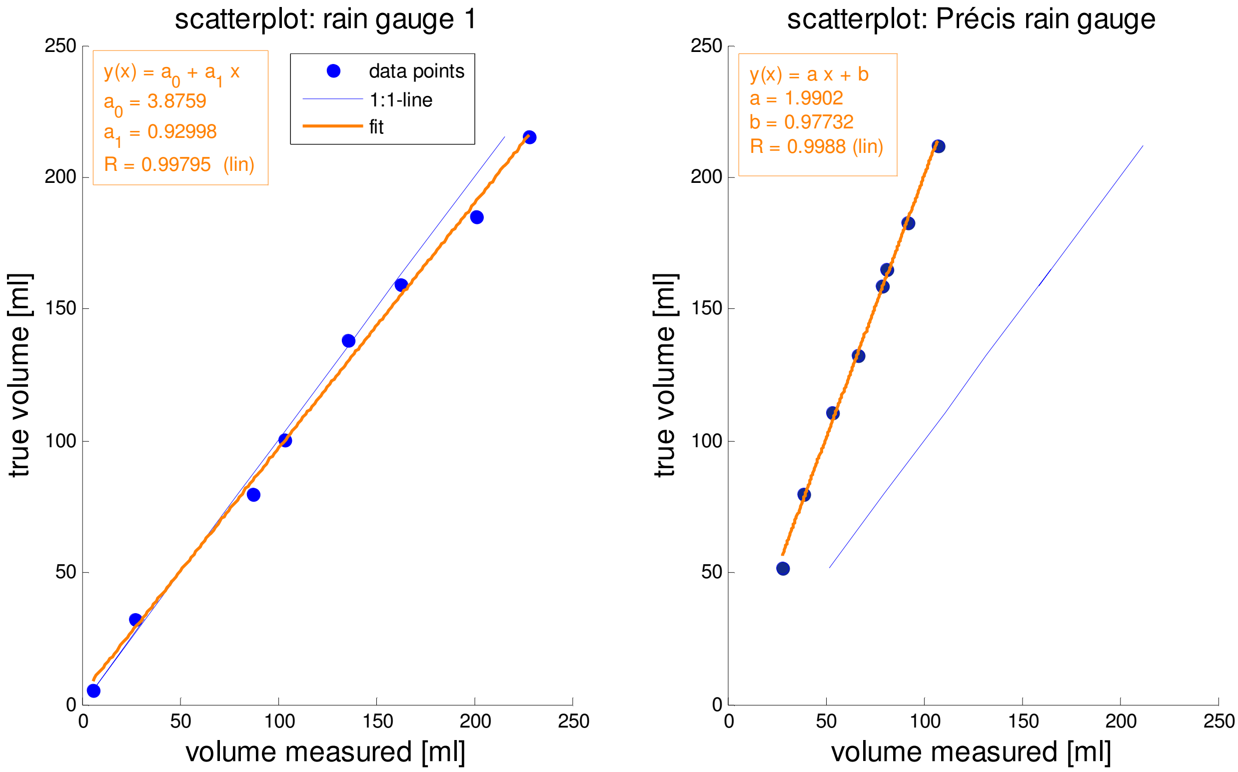


Figure 12-comparison of the measured volume to the "true volume"

In the first graph the fitted curve is quite close to the 1:1 ratio line. Only two points are above the curve, which correspond to underestimations. All the other are measurements that overestimate the "true volume". The second graph is showing the data of the précis rain gauge. The curve is situated clearly above the 1:1 ratio line and all the measured values are lower than the actual volume. However, the linear curve fits the line quite well and the relationship may be used to eliminate the errors. In the table below the relative deviations of the measurements to the actual value (1:1 line) are listed.

Table 10-relative differences

II B 11th June- various pumping times

time per run [min]	5	10	15	20	25	30	35	40	min	max
1	15.78%	1.71%	-9.11%	-2.97%	1.53%	-2.44%	-8.66%	-5.91%	-9.11%	15.78%
precis		46.32%	51.78%	51.74%	49.86%	50.15%	49.67%	49.55%	46.32%	51.78%

As expected, the deviations of the measurements of the sensorscope rain gauge are rather small as compared to the deviations of the précis rain gauge. Again, the latter have values around 50%.

The pumping rates in this experiment vary between 0.23 and 0.3 mm/min. In the histogram below are shown the frequency of intensities measured by all the stations during the year 2010. The interval corresponding to the pumping rates of the third part of the experiment were added as well. Obviously, the pumping rates include intensities which are neither very frequent nor very rare.

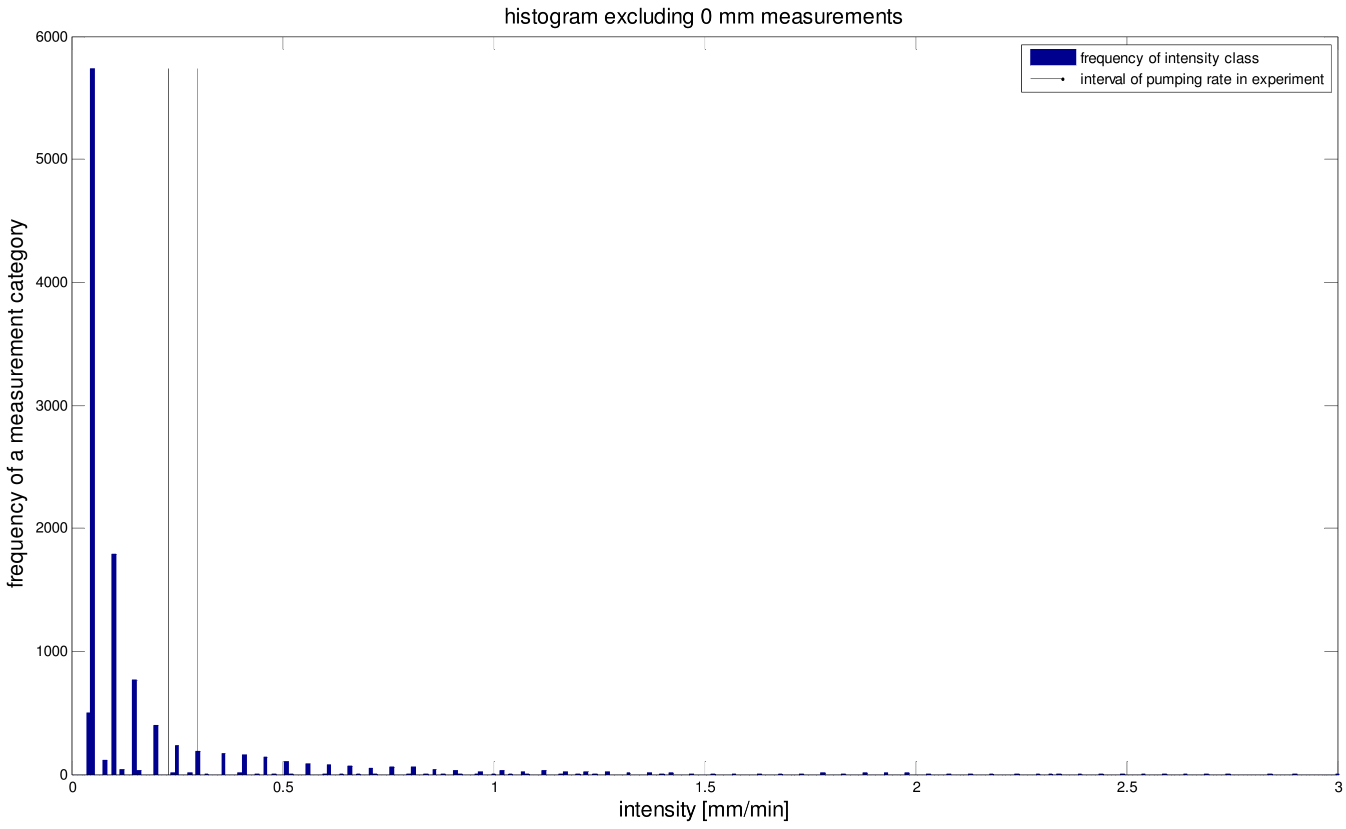


Figure 13-Histogram of the rain rates measured in the year 2010

On the histogram is not shown the relative importance of these intensities in terms of amount of rain. If the frequency is multiplied with the amounts measured, the importance of higher intensity may become larger. This is shown in the figure below. The intensity classes on the right hand side of the interval become more important. The relative importance of the amount of rain measured within the range of intensities corresponding to the pumping rates to the total amount measured is 3.6 %.

2.4.2 Discussion

In general, the results obtained from this experiment apply only for low intensities. As already observed in previous experiments, the errors of underestimation are large. This is the case, especially when the rain gauge is saturated with water.

Regarding the low intensities, it can be concluded that the errors in measurement of the sensorscope rain gauges are very variable and the error range is of about +- 15%. As the number of the error values is not enough, this range can be set only qualitatively. In order to get a better estimate of the error range, the experiment has to be repeated many times and then a statistical method can be applied considering the distribution of the errors.

Astonishingly, the measurement error of the précis rain gauge was always rather constant. In the first experiments, the relative underestimation was about 51-52% and in the experiment with the scale, which is considered being more accurate, the underestimation of the true value was around 50%. This means that the precision of measurement is high, but the measurement itself is incorrect. Hence the correction of the data is straight forward, by applying a correction factor of 1.5 for the précis rain gauge.

2.5 Conclusion

My experiments in both the laboratory and in the field suggest that all data from a Davis rain guage an error range of +-15% needs to be applied. For higher intensities underestimation is more probably, due to the malfunctioning of the mechanic parts in the rain gauge (cf. sources of error). As for the précis, the underestimation is constant. In the manual was found, that underestimation only occurs for high intensity. However, also at low intensities, the true volume was underestimated by about 50%. All the experiments in the laboratory confirm this. The error is larger, than the value indicated by Civiate and Mandel (+-10%).

As for the stations in Tambarga, it must be taken into account that additional factors such as wind, can falsify the measurements. The experiments were designed to exclude other influences in order to evaluate exclusively the instrumental error.

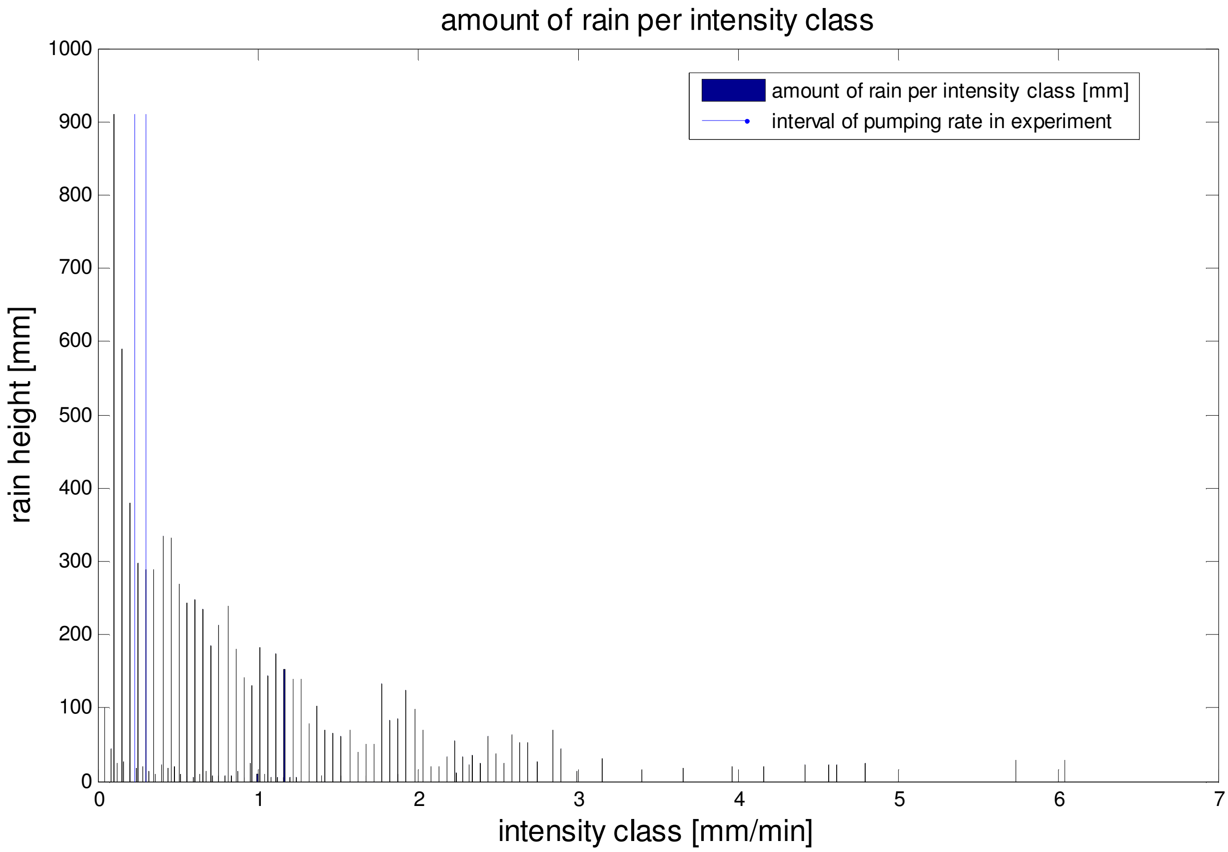


Figure 14-the cumulative rain height per intensity class over the year 2010

3 Rain measurement- in space (stations) and in time (seasonal patterns)

Interest

The rain data of the sensorcope stations is considered in this section. The behavior of the stations is analyzed so as to select reliable stations, which data can be used in the analysis of this thesis. Then, using the data of the selected stations, the seasonal pattern of the rain is displayed. Comparison with another study shows the limits imposed by the availability of data. As the stations did not work during the month of October, the end of the rainy season can be determined. Finally, based on this data, the rain events for the period from May to August are identified following specific criteria.

Method

The data is first evaluated by visual analysis. In a second step the problem of communications errors is addressed. The method consists of determining the periods at which the stations did not record any data and the frequency of communication problems which determines their reliability.

3.1 Behavior of the stations

To compare the data of the different stations, the cumulative rainfall is calculated for each station at the 5 minutes time step. The result is shown in the graphs below. The final value of each curve in the month of October corresponds to the total amount of rain measured throughout the year. The stations stopped working in October or November. On the first graph, only the stations in the valley are shown. Station 1015 (magenta) already stopped working at the beginning of September. The stations measure approximately the same amount of rain. A certain local variability is observed, but the increase of the cumulative rainfall measured is always observed simultaneously. Station 1008 measured considerably less in the months of June and July but increases afterwards, in August and September, at a similar rate than the other stations.

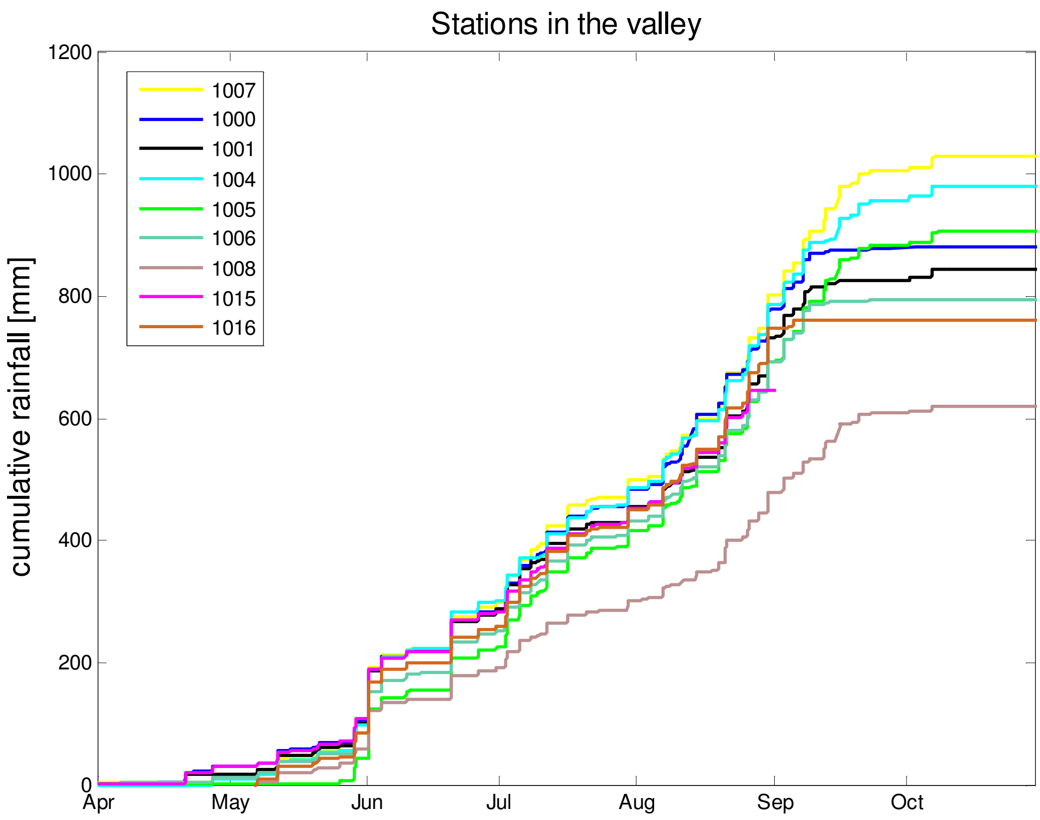


Figure 15

The second graph depicts the cumulative rainfall of the stations situated on the hill. Station 1014 measured significantly more than the other two stations. If this station was plotted at the above graph, it would appear above the highest curve (station 1007). Station 1014 is situated on the hill and is highly exposed, as no trees are in proximity. The exposure is certainly a reason why more rain is caught by the rain gauge. Station 1010 stopped working ending September.

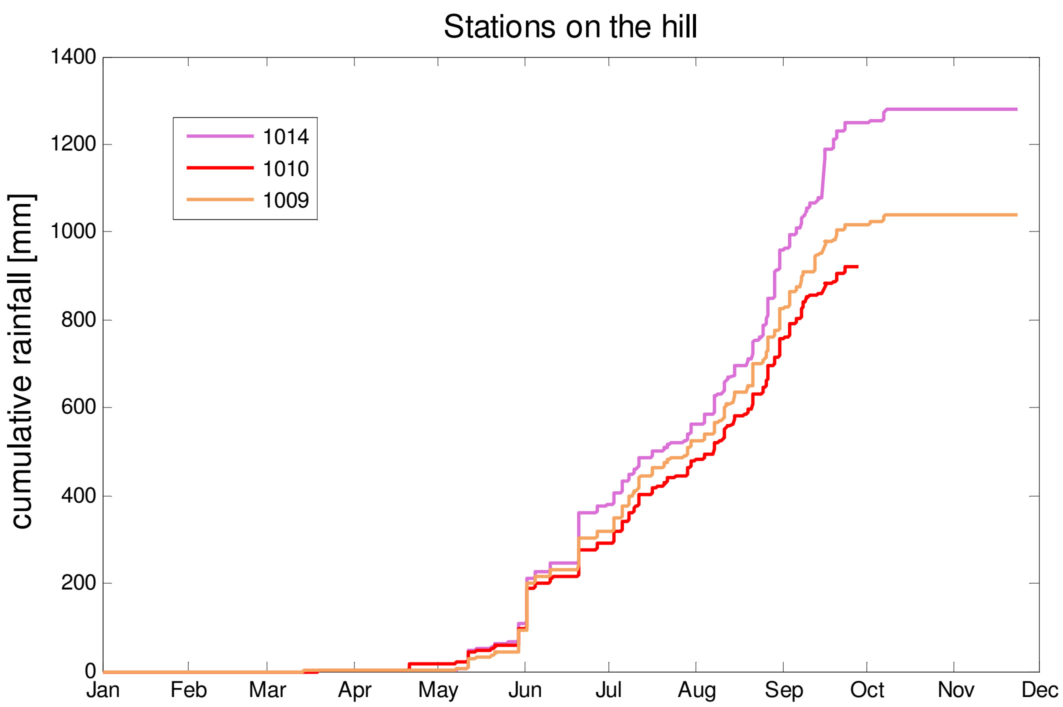


Figure 16

3.2 Choosing the dataset

The assumption was made, that the measurements by the stations are correct, if the stations are working or that the error can be estimated and corrected in the contrary case. Then, the problem that remains is the interruption of measurements due to communication problems. In this section, the communication problems are examined for each station. The period considered is the 1st April till the 10th October 2010. The end date corresponds to the date at which all stations started having problems. They did not work between the 10th October and the 29th October 2010. Therefore no data is available for this period of time. The period was chosen so as to cover the best possible the rainy season. The objective is to determine the periods when the communication problems occur and see if they fall inside the rain period.

The stations were considered one by one. Two types of problems exist:

- interruption in the measurement of time. Consequently, no rain was measured either.

- communication problems which occurred between the rain gauge and the station (time is measured but rain is not).

The rain measurement interruption occurred often only one single time (one NaN appearing in the vector) and then not anymore, which gives over the whole year rather a dispersed pattern. The interruption of the time measurements, on the other hand, corresponds most often to a continuous interval which is easily detectable.

The distribution in time of the NaN values (due to the first problem type) were visualized on graphs which are not shown here. The table below shows how many times such a communication problem occurred for each station.

Table 11 – number of NaNs per station

stations:	1000	1001	1004	1005	1006	1007	1008	1009	1010	1014	1015	1016
estimation NaN	343	49	50	51	91	66	61	47	34	101	40	66

The second type of problem is easier to deal with. The time intervals during which the interruption of measurements occurred are listed in the below table. The reliability of the stations was evaluated. Two stations, station 1000 and 1006, are not considered being reliable. Both stations presented many interruptions of measurements for longer than 30 minutes. Other stations can be used but only for certain periods (partially). The number of NaNs is also large for station 1014 which may be caused by the wind or the high exposure to other meteorological factors (radiation etc.). Four stations (1001, 1008, 1009 and 1015) cover a long time and are almost constantly working. These are the most reliable stations.

Table 12- evaluation of stations

station	reliable	period	reason/comments
1000	no	-	measurement errors
1001	yes	21.03.2010-09.10.2010	few NaNs, good time coverage
1004	maybe (partially)	26.04.2010-09.10.2010	few NaNs
1005	maybe (partially)	01.01.2010-06.05.2010 and 21.05.2010-09.10.2010	Few NaNs,large interruption
1006	no	01.01.2010-09.04.2010 and 23.04.2010-28.10.2010	large interruption and smaller ones
1007	maybe (partially)	01.01.2010-25.03.2010 and 23.04.2010-09.10.2010	few NaNs
1008	yes	01.01.2010-09.10.2010	few NaNs, good time coverage
1009	yes	01.01.2010-09.10.2011	few NaNs, good time coverage
1010	maybe (partially)	01.01.2010-10.04.2010 and 06.05.2010-09.10.2010	few NaNs
1014	rather not	01.01.2010-24.03.2010 and 05.05.2010-09.10.2011	some NaNs
1015	yes (partially)	28.02.2020-01.09.2010	few NaNs, almost optimal time coverage
1016	maybe (partially)	06.05.2010-09.10.2010	few NaNs

The functioning of the stations was also analyzed regarding the rain events. If a station was not working during an event, it was not used for the whole month. The following table shows the months for which the stations can be used. The green color indicates that a station can be used for the month considered. The stations were regrouped in the three sub-basins: close to the outlet of the river (1001, 1008), in the valley (1004, 1005, 1007, 1015 and 1016) and on the hill (1009, 1010, 1014). The total number of reliable stations per sub basin is counted and the number appears in the last column of the group. The total of stations is the number of stations which finally can be used for the month considered.

Table 13-stations selected for specific months

data set	1001	1008	1004	1005	1007	1015	1016	1009	1010	1014	Total of stations
March		1					2			3	6
April		1					2				3
May		2					4			3	9
June		2					5			3	10
July		2					4			3	9
August		2					4			3	9
September											0
October											0

Only during the month of June, all the stations were working. As for the months May, July and August, one single station needs to be excluded. Therefore the period of study was chosen to be the period from May to August.The selected stations are all the ten stations that figure on the table with the exception of station 1005 (excluded for the month of May), station 1004 (excluded for July) and station 1015 (excluded for August).

3.3 The evolution of rainfall in time (seasonal pattern)

The figures below show the evolution of monthly rainfall during the year. On the graph on the left hand side is shown the boxplot of the monthly rainfall measured for the stations considered being reliable. Only the period which will be used for further analysis in the subsequent sections is displayed. On the right hand side a graph is shown depicting the rainfall for a longer time period. These stations were working well throughout the year. However the station 1009 stopped working before October. This graphs show the seasonal pattern of rainfall in Tambarga. The rainfall in August is at its maximum. Also the frequency of events is highest during this month. Comparing both graphs, it can be observed that the rainfall measured in July is little less than in June.

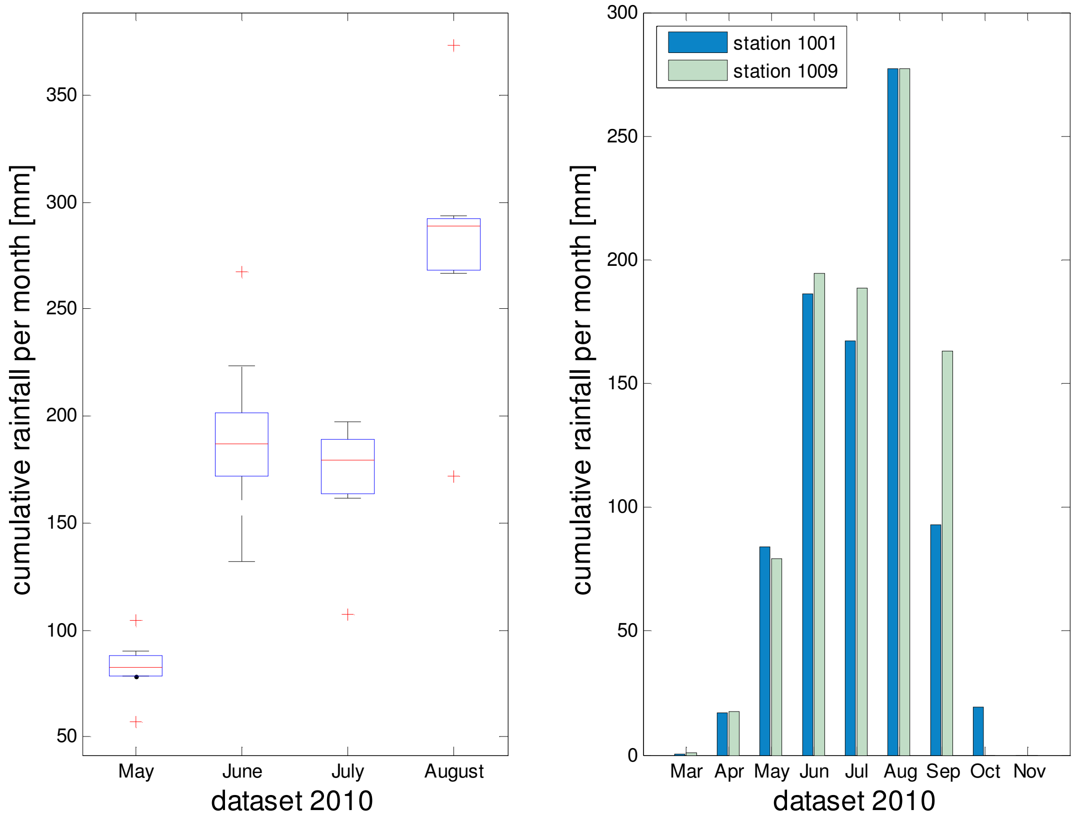


Figure 17

Lucio et al. investigated the seasonal pattern of rainfall more in detail. It was suggested that the regime can be decomposed in three regimes: the dry season, a transition period and the rainy season. A similar graph was obtained for a station situated in Ougihoua (Burkina Faso). Instead of looking at different stations, as it is the case in the boxplot above, the series of data consisted of 50 years of data (1950-2000). Therefore, the variance is considerably high.

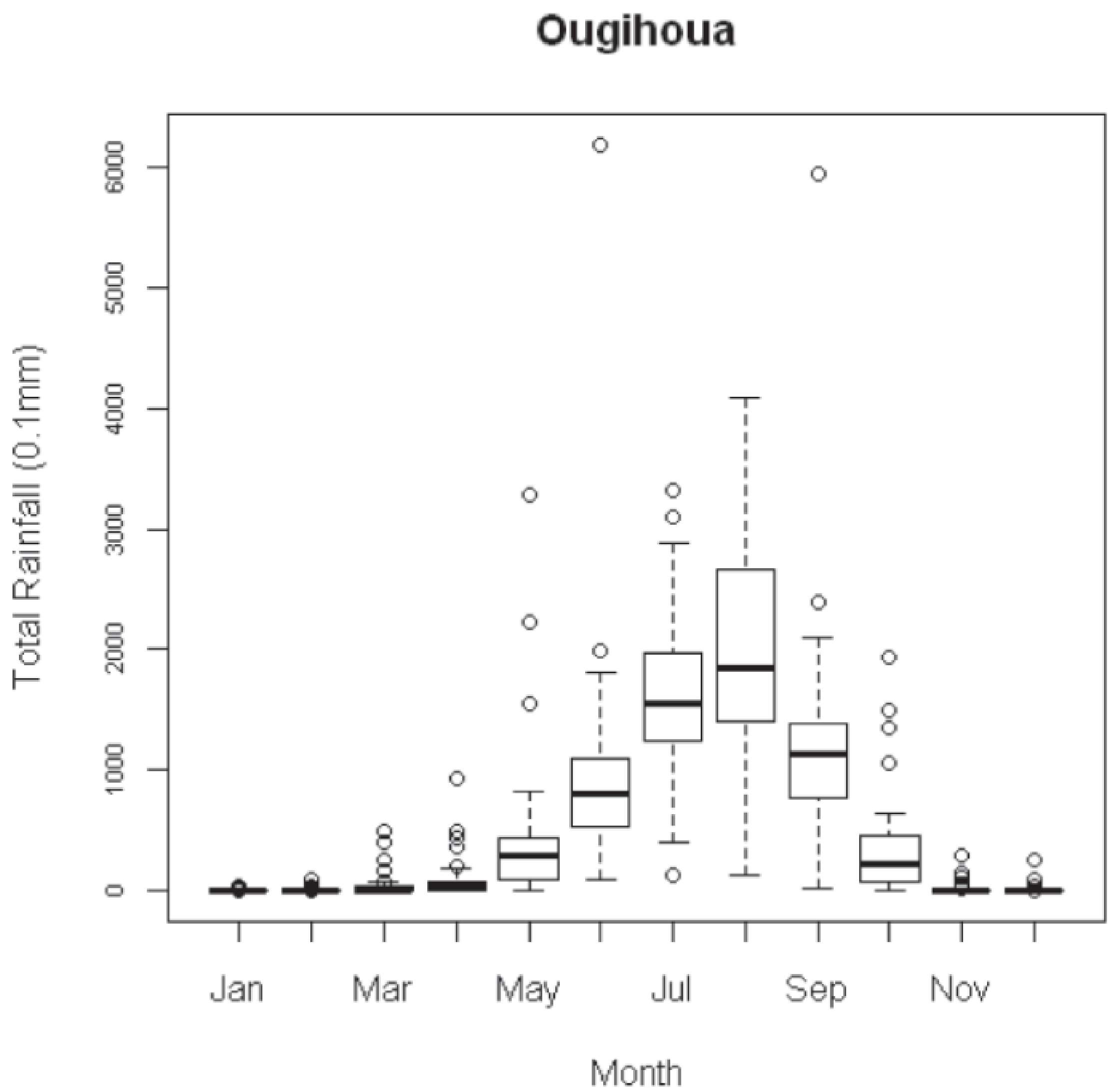


Figure 18

The seasonal pattern is similar to one in Tambarga. It should be noted that the units on the y-axis are in 0.1 mm. The graph shows that the monthly rain in July is generally higher than in June. By contrast, in Tambarga the rain measured in June is higher than in July, but the values are similar. This difference can be explained considering the evolution of rain at a smaller time scale.

3.4 Identification of events

The criteria defined by Thierry Lebel (2009) were used for the identification of the events[12]:

1. The cumulative rainfall of an event is at minimum 1 mm.
2. If for two events the dry period separating them exceeds 30 minutes, they are considered as two distinct events.

These criteria were applied at all the stations and only those events are retained by which at least by the 50% of the station 1 mm rainfall was measured.

The figure below shows the evolution of the rain events and the corresponding cumulative rainfall height measured for the stations selected from May to August 2010. In June, the frequency of events is lower. During this month two high intensity rain events (1st of June and 20th of June) are identified. Their contribution is important in the monthly rainfall accumulation which overweighs the cumulative rainfall observed for the month of July. In May and June, the frequency of the rain events is lower and they are more irregularly distributed. By contrast, the rain events succeed each other more closely in July and August. In August, sometimes more than one rain events happen during a day.

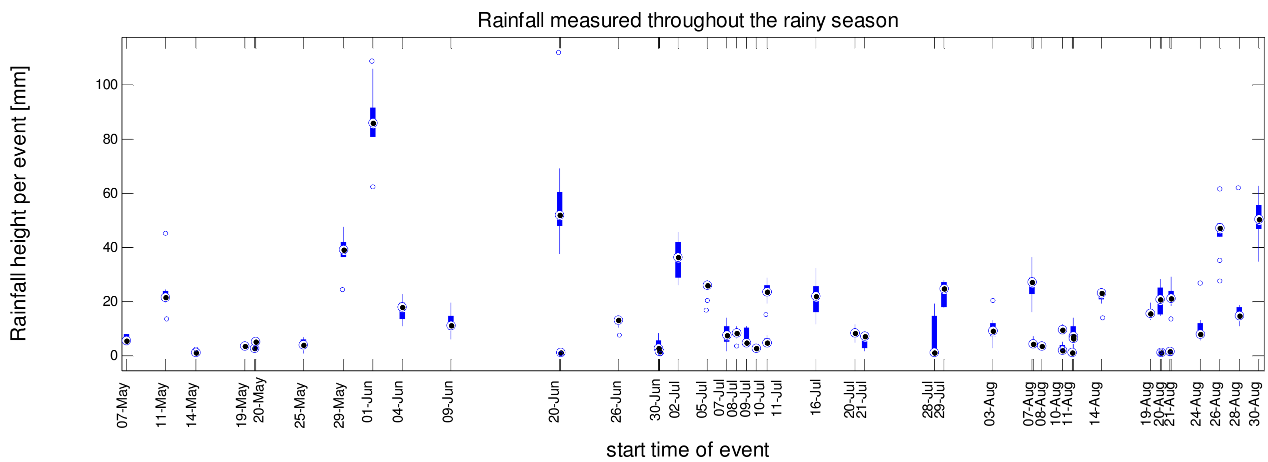


Figure 19

[12] Recent trends in the Western and Central Sahel rainfall regime (1990–2007). Thierry Lebel, Abdou. Ali. doi:10.1016/j.jhydrol.2008.11.030.

3.5 Conclusion

The final dataset consists of the data from ten stations (1001, 1008, 1004, 1005, 1007, 1015, 1016, 1009, 1010 and 1014). They can be used for the period from May to August. Exceptions are station 1005 did not work for certain events in the month of May, station 1004 for the month of July and station 1015 for the month of August.This can be taken into account in the analyses of the following sections.

Totally 49 rain events were identified for the period considered. The events are numerated chronologically and the corresponding dates can be found in the table added in the appendix. In the following the individual events are referred with their corresponding number and not with the date.

4 Interviews in Tambarga

4.1 Implications

The indigenous knowledge is local knowledge that has been passed on from one generation to the other. It is said that the indigenous knowledge is not transferable, but provides relationships that connect people directly to their environments and the changes that occur within it.[13] This knowledge is crucial. The decisions which are taken by farmers are relying on it. The indigenous knowledge is of importance also for any person who aims to improve the conditions of rural communities. It has to be included in the design of development projects.

One major concern is the climate change and its impacts in the Sahel region. This region is considered being very vulnerable to climate change because it is regularly affected by droughts. It is difficult to quantify the impact of climate change on the communities in the Sahel region. It can be predicted that the temperature will increase, but the change in the precipitation pattern is unknown. On one hand the Sahel seems to be a vulnerable region, on the other hand the capability to adapt to changes in climate is high, because the climate variability is also considerable in the Sahel region. The people have developed over a long time different strategies to adapt and this skills are integrated in the indigenous knowledge.

4.2 Objective

The objective of the interviews was to investigate how the indigenous people in Tambarga perceive rain and to see how this knowledge is related to the observations in our research. This may in turn improve the overall knowledge on rainfall characteristics. As the researchers only stay at the field of study for a short time, one or two seasons, and not always in entirely. The indigenous knowledge, which developed over a very large time scale, is crucial. This survey may also help to better understand the point of view of the villagers and which factors related to rain are important to them.

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[13] A. Nyong, F. Adesina, and B. O. Elasha, "The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel," *Mitigation and Adaptation Strategies for Global Change*, vol. 12, no. 5, pp. 787–797, 2007.

4.3 Method

The questionnaire was composed of ten questions related to the period, the frequency and the type of rain as well as its effects. The interviews were conducted orally with the assistance of a local interpreter who translated from French to Gourmantché and vice versa. Persons living in Tambarga were interviewed. To ensure certain representativeness in space, never two persons living in the same house were questioned. Moreover, each day, another part of the village was visited. As a total, 30 villagers were asked to give their point of view (11 women and 29 men). The age of the respondents is unknown, but the focus was put on the elder people of the village who have more experience.

4.4 Results

It is important to mention that the interviews were carried out in February 2012, during the dry season which followed a drought rainy season. The answers were affected by their worries about the absence of rain of the last year and the fear of the desertification.

In the first part of this study, the rainy season and the evolution of the number of rainy events is considered. The chart below shows the time period of the rainy season according to the thirty individuals. The blue lines correspond to the time intervals. When they were being asked when the rainy season starts or ends the answers were like: “early April”, “mid June”or “ending October”. To present this graphically, the light blue line stops accordingly before the end of the month (e.g. ending October) or starts later (e.g. early April). Most persons interrogated indicated the time period of the rainy season to last from May to October. Thus in the graph the interval is represented starting at the beginning of May and stops at the end of October. The month of May is for 66.6% of the sample the starting month and October was for 63% the ending month.

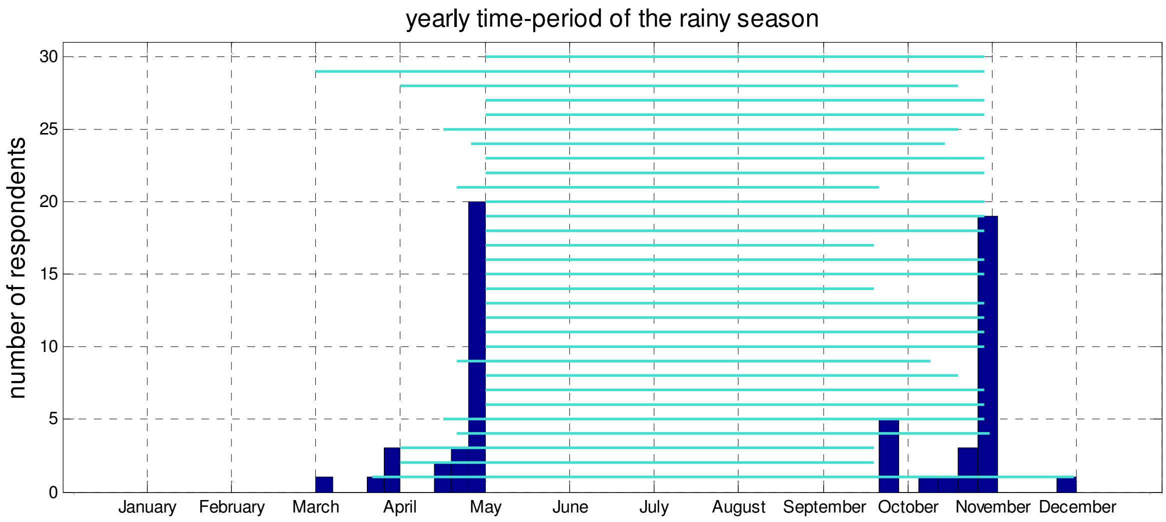

Figure 20

The answers are based on several years of observations, whereas in the dataset of the Master's project, only the year 2010 is included. There were only few events observed in March and April and the number increases with time, with the highest frequency in August. The months September and October weren't analyzed because less data was available. The end of the rainy season can't therefore be defined and compared to the results obtained here.

The definition of the rainy season is not clear and to assess the limits scientifically, criteria have to be specified. Frappart et al. used the following criteria: "The beginning of the rainy season is defined by the first occurrence of at least 20 mm cumulative rainfall in 3 days, after the 1st of May, and not followed by more than 7 successive days without rain within the 30 following days. The end of the rainy season is determined by the occurrence of 20 successive days without rain, after the 1st of September."[14]

Another interesting question is the evolution of the rainy days throughout the year. In this study, the years 2009, 2010 and 2011 were considered. The results are shown in the figure below. The answers varied considerably. However, the seasonal pattern is similar for all three years with only few rainy days at the beginning of the season and its maximum in August after which the number declines again. In 2009 the peak is more pronounced than the other years. It was the wettest year, and during the two following years the rain tended to decrease. The standard deviation in the month of August is also very large in 2009 and smaller for the

[14] Frappart, F., Hiernaux, P., Guichard, F., Mougin, E., Kergoat, L., Arjounin, M., Lavenu, F., Koité, M., Paturel, J. E., and Lebel, T.: Rainfall regime across the Sahel band in the Gurma region, Mali, J. Hydrol., 375(1–2), 128–142, http://dx.doi.org/10.1016/j.jhydrol.2009.03.007,2009

other years. The generally large values of standard deviation obtained for this month might be due to the fact that it is difficult to estimate the number of rainy days. Some villagers said that in August it was raining all the time, but most often it wasn't heavy rain. The flat curve in 2011 is in accordance with the statement of 2011 being a year with little rain during the rainy season. On the graph of 2010, additional to the errorbars, the number of rainy days as calculated from the data of the sensorscope stations is represented with green diamonds. The value is always larger than the mean value obtained by the survey whatever month considered.

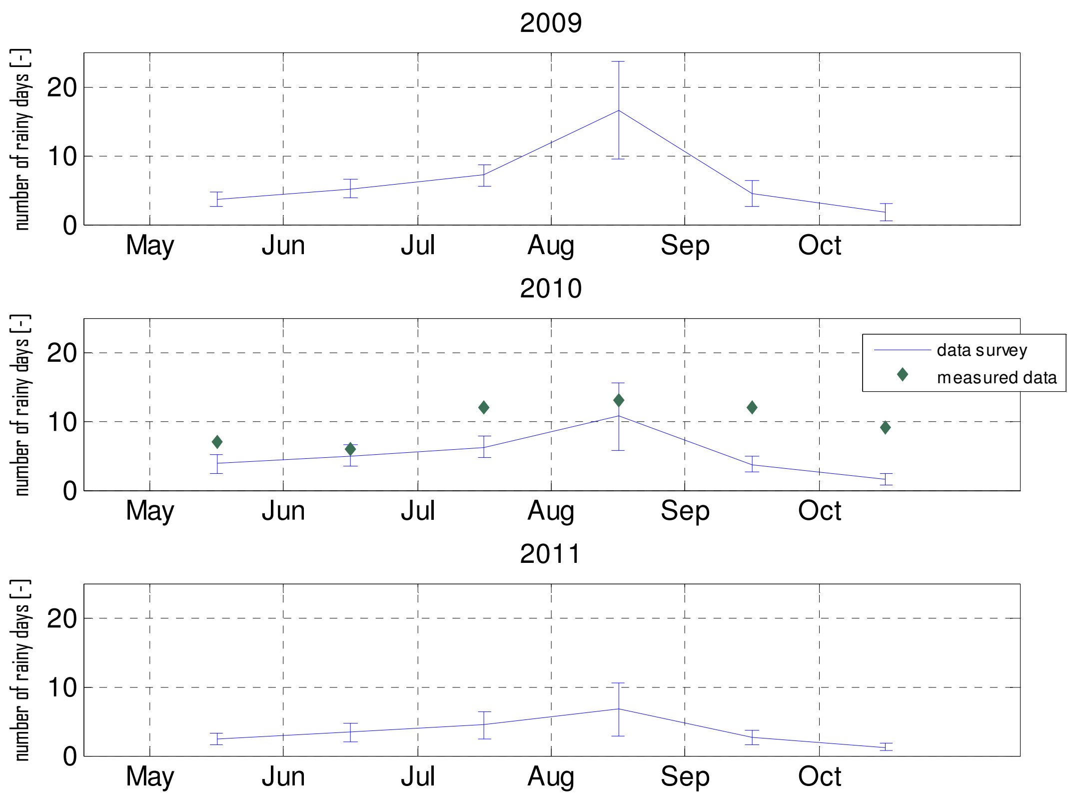

Figure 21

There is a significant change in the number of rainy days. This leads to the question, if the farmers also think that the time period of the rainy season has changed in recent years. The answers varied considerably, which is certainly partly due to the fact that the villagers have a different opinion on how the onset and the end of the rainy season are determined. The rainy season is perceived as a period during which rain events succeed each other at a certain rate and the amount of rain fallen is rather high. Thus, three categories of answers were established. The first category encloses answers concerning the quantity of rain, which is also one of the indicators used to delimitate of the rainy season. In general, the tendency is that the quantity has been declining in recent years. Especially, the year 2011 was a dry year, but it is also thought that 2009 and 2010 were rather dry years. A few respondents explained further the general situation. They said that their lives changed substantially, and that the desert is advancing. They are worried because resources of water are diminished. Totally, 73% of the interviewees were talking about this negative decreasing trend of the amount of rain.

The second category is the irregularity of the distribution of rain events in time. More precisely, the farmers are affected by the problem that the rain sometimes had stopped over several days and if they had already started with cultivation the seeds got lost.

The decrease of quantity of rain in the early months of the year can also be translated in shift of the beginning of the rainy season. Likewise, if after some rain events in the early year, it stops raining for several days, these events are not considered as being a part of the rainy season and the beginning of the rainy season is later in the year. However, even if these three categories are somewhat related with each other and correspond to similar observations, they were separated in order to reveal different points of view. Particularly, except one person, all respondents said that the rainy season started only in the month of June, which represents a large change. In the first graph showing the time periods of the rainy season the starting month was in not in a single case later than May. This shows that this late start was rather unexpected. Some farmers also affirmed that they couldn’t sow before the month of June, because of the missing rain. Only one of the respondents said that the end was also shifted in time.

The second part of this study deals the different rain types as perceived by the people living in Tambarga. The questions were open-ended, such that the answers reflect truly their point of view. They help to reveal the way the people perceive their environment and organize their thoughts. Hence, the way they differentiate between rain types is highly variable. Already, the number of different rain types they distinguish varies considerably. In the figure x. is shown the percentage of individuals as a function to which degree they differentiate (the number of different rain types they mentioned).

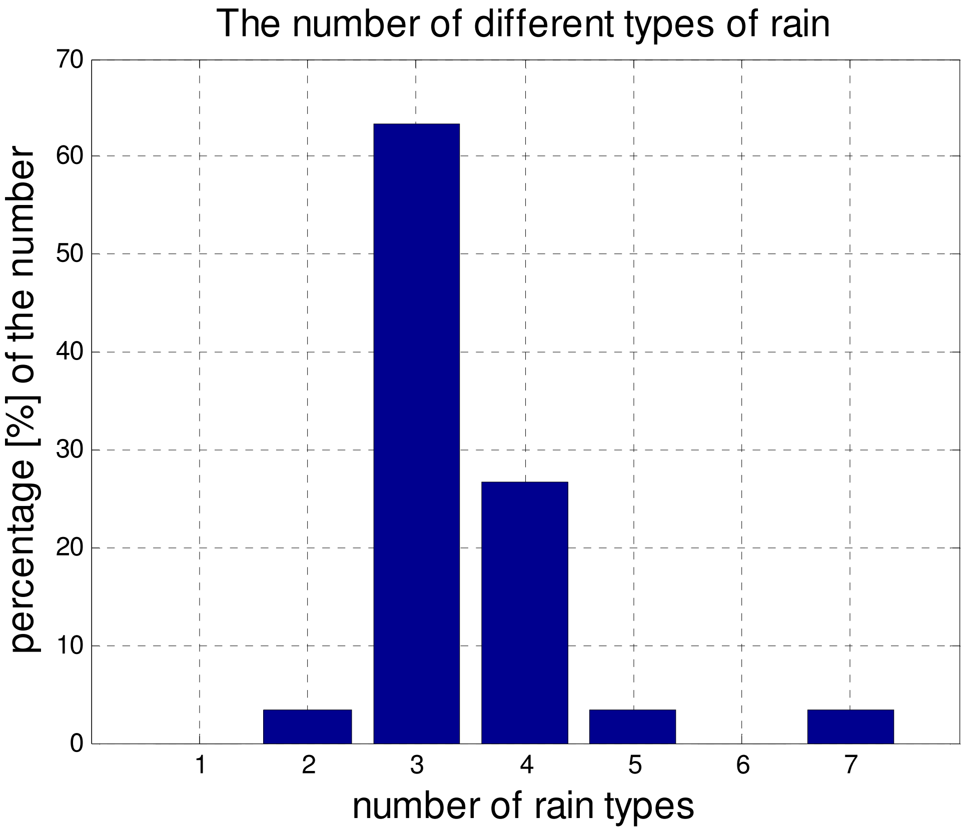

Figure 22- frequency of the number of different rain types described by one individual

By far the most villagers identified at least 3 different rain types. The maximum of different rain types was 7. They were not only asked to tell how many different rain types they know, but also to explain the different types. This information is used to establish a classification:

Ordinary rain:

R) large/heavy rain r) small rain

Extraordinary rain:

H) Hail (3.3%)

E) rain invoked by humans (extraordinary rain) (33%)

In the case of the ordinary rain only (groups r and R), it was further differentiated into smaller categories. The following table gives an overview.

Table 14- Classification of rain types

ordinary rain	R) heavy rain	r) light rain
w. without wind	a)heavy rain (hr) (63.3%)	a) light rain (lr) (83.3%)
	b) short and intense rain (sd) (3.3%)	b) very light rain (vlr)(3.3%)
	c) rain with runoff (rnf) (3.3%)	
	d) rain with pooling (pool formation) (pol) (3.3%)	
	e) thunderstorm and heavy rain (thu) (6.6%)	
W. with wind	a) heavy rain - strong wind (sw) (13.33%)	a) light rain- short duration(sd) (26.6%)
	b) heavy rain- wind (w) (36.6%)	b) light rain with wind storm (ws) (13.3%)
	c) windstorm and heavy rain (ws) (10%)	
	d) tornados (t) (36.6%)	

In the vertical direction (rows), the principal distinction is made based on wind. Certain rain types are accompanied with wind and others are not. Actually, the wind was only mentioned for the rain types of the class W. However, it was assumed that in class w, the wind was not important and if it wasn't mentioned there is no strong wind or no wind at all for the rain type considered. In the horizontal direction (columns), the rain types are distinguished following the quantity. The rain is not measured by the villagers, but they discriminate between little rain and heavy rain. In the following the different types of rain are indicated using the nomenclature derived from the table above. For instance, the rain type "windstorm and heavy rain" is called type RW-ws. The color scale applied here gives an idea of how many people described a certain type of rain. The figure x shows the percentage of people interrogated who mentioned a certain type of rain. At the first sight, the dominating types are clearly the Rw-hr and the rw-lr type. From this, it can be deduced the quantity of rain is the variable which the farmers interest the most. In addition, these two classes correspond to a low level of discrimination. Other classes seem to be less important because only few individuals described the rain events in more detail. A special case represents the types which are described by the consequences of the rain rather than the rain itself. These types are Rw-rnf and Rw-pol and only 3% of the villagers were considering these. Types of rain which are accompanied with wind such as RW-w, RW-t and rW-st are also frequently mentioned. Generally, the wind was mentioned by many inhabitants of Tambarga, because of the danger it represents. Sometimes houses are destroyed, and the wind can also take down trees and fields. The rain invoked by humans is a special rain type which can happen at any moment. This rain has different purposes. The rain is useful to irrigate the crops. In the case if somebody has stolen from another farmer, the corresponding rain event is rather of stormy nature and the thunder punishes the person in question.

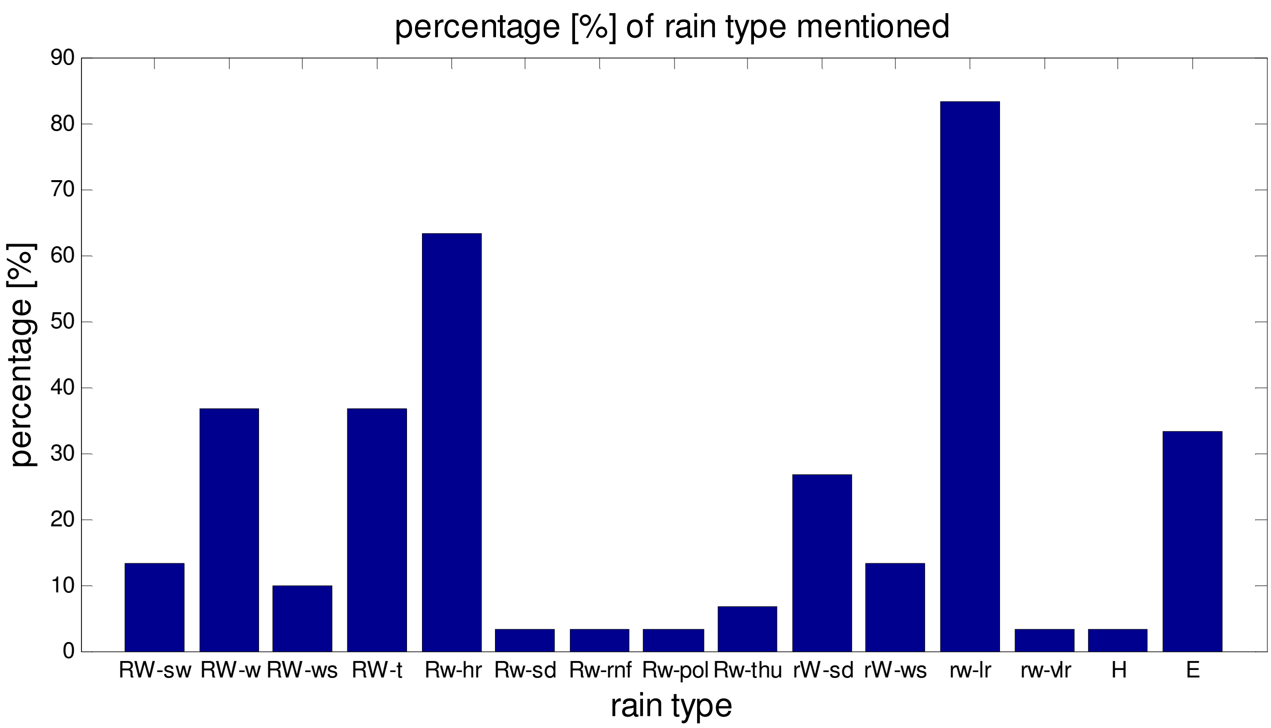

Figure 23- frequency of rain type mentioned in the survey

In a first step, the rain types occurring during the rainy season are examined. The month at which they take place, their duration and the intensity are the parameters considered.

The number of times at which a certain month was associated with a rain type was counted and the results are expressed in percentage of the total population. The figure below displays the results. The months concerned vary sometimes with the type of rain. The blue and green colors correspond to the heavy rain category and the warm colors correspond to the categories of small rain as well as extraordinary rain. A particular case, the rain invoked by humans can occur at any moment and its percentage is about 33.3% because 10 persons were talking about this type of rain (and equals a third of the sample). It is important to be mentioned, that this graph represents the fraction of people talking describing a certain rain type and associating it to a certain month. Thus, even if a raintype represents a high percentage at a certain month considered, it may be rather due to the fact that many people were talking about this rain type than to its frequency of occurrence at a certain month. However, if comparing the evolution during the rainy season of one rain type to another certain relationships can be revealed. The heavy rain types are frequently observed in the months of May (type RW-w: 26.6%), June (type RW-w and Rw-hr: 23.3%), July (type Rw-hr: 36.6%) and September (type Rw-hr: 36.6%). In August the light rain is the type that is by far the most frequent. This is in accordance with what the people said about the month of August. They described it as a month during which it rains all day, but most often only little rain is falling and heavy rain may also fall, but this is rather rare.. Light rain with wind is most often observed in the months of May and September (rW type). In October only few rain is observed and exclusively light rain which is sometimes accompanied by wind. The heavy rain type associated with wind may occur in the period from May to September. In May, this type of rain is less frequent, which is not surprising, as it is the beginning of the season. Tornados are most probable appearing in July. By contrast, the month of August is generally less windy than the other months.

Short and intense rain (Rw-sd) and rain with runoff (Rw-rnf) are not easily distinguishable on the bar chart, because of their respective colors. However, this doesn't pose a problem because they are never observed at the same month. The Rw-sd type (short and intense rain) occurs in May and June and the Rw-rnf type (rain with runoff) in July and August. Only few persons were talking about these types and the rain with pooling type (3% of the population).

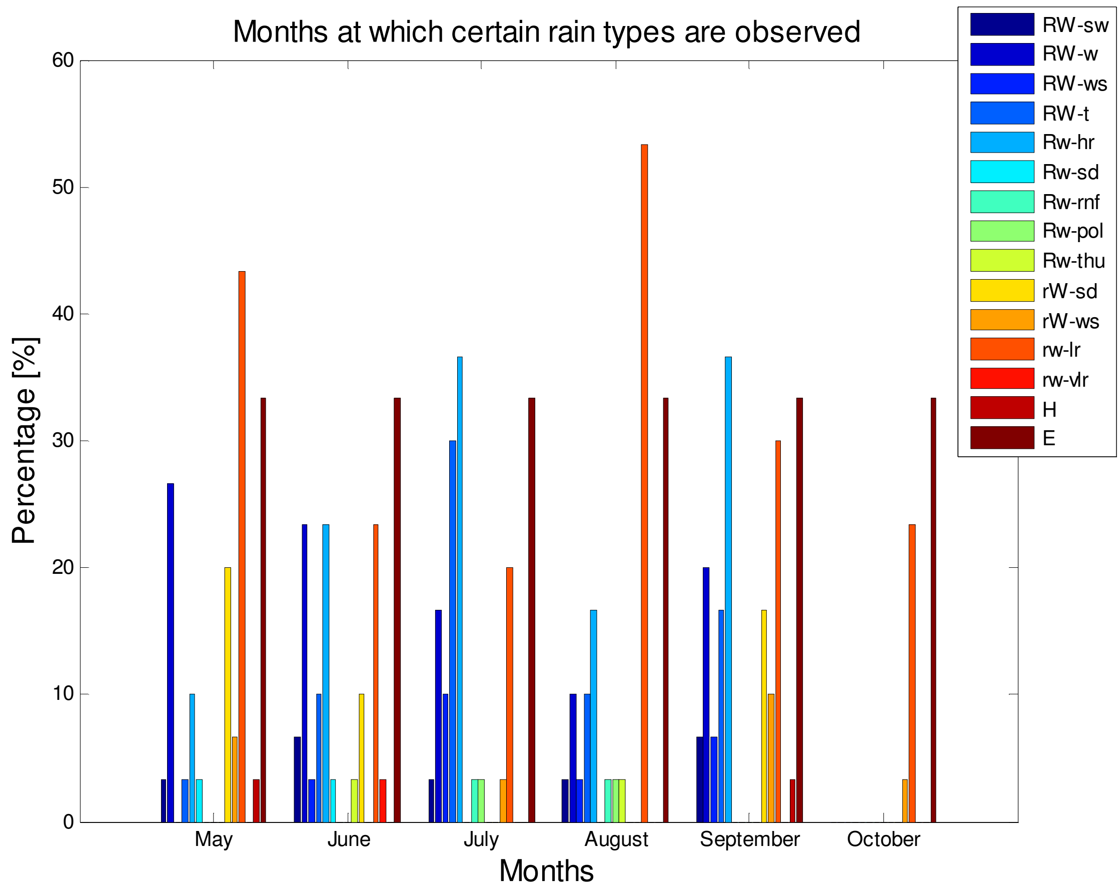

Figure 24- months at which a certain raintype is associated

The rain durations were also investigated and the results are shown in the graphs below. The first graph is a boxplot of the rain durations as a function of the rain type. The second graph is an errorbar plot displaying the mean values and the standard deviation of the duration series per rain type.

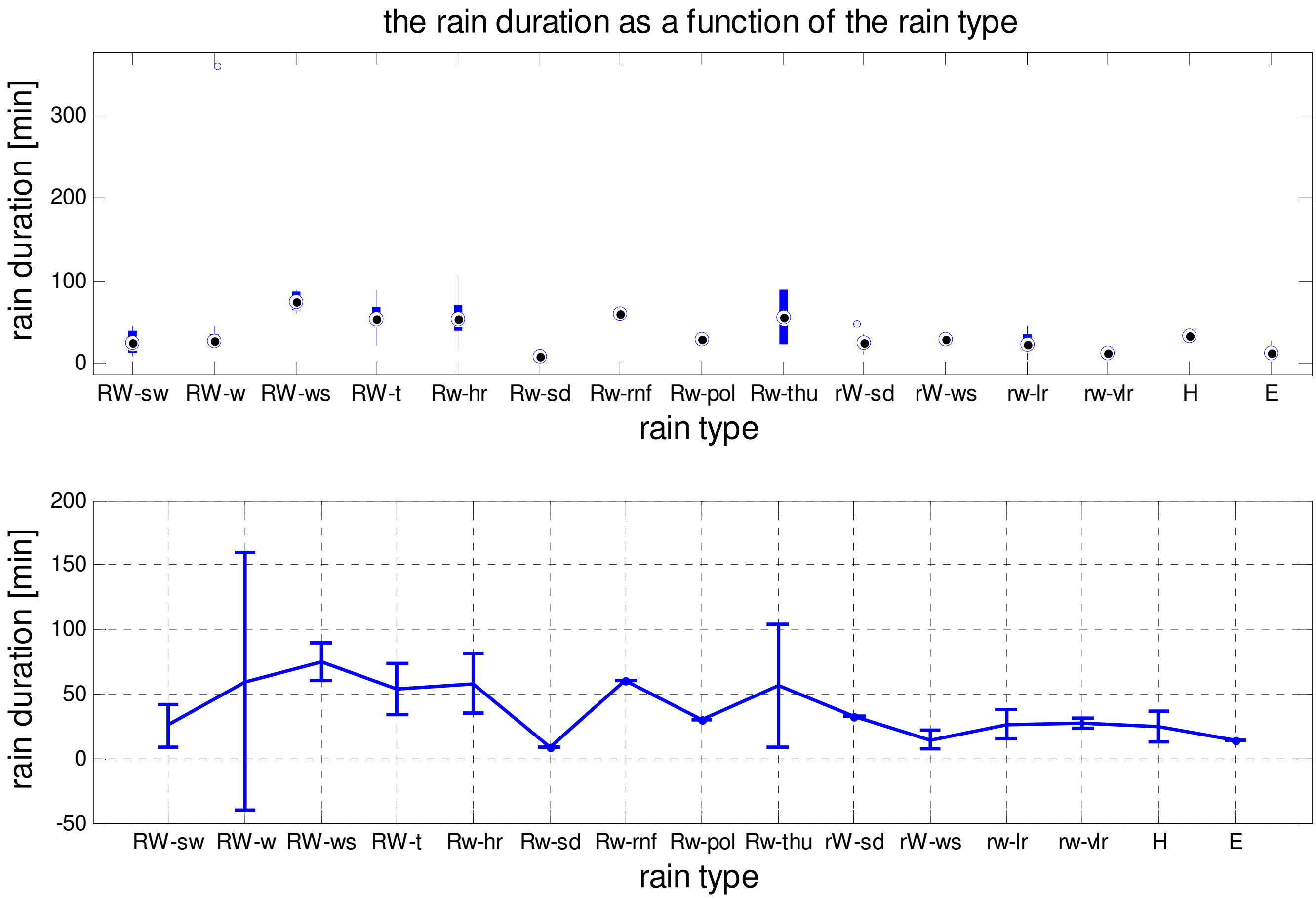

Figure 25- The duration of the different rain types

One single person said that the heavy rain with wind (RW-w type) can last for 6 hours. This value is very large such that on the box plot, the other values are quite not visible. Moreover the standard deviation for the series of this rain type is very high. As a consequence, negative values were included in the interval on the errorplot. For these reasons this aberrant value was removed and the corresponding boxplot is the figure below. As the sample size is rather small, other extreme values have not been removed. The second graph shows the number values used for the computation of each boxplot and each error bar.

If the answers diverge a lot, the standard deviation is very high, as it is for instance the case for type RW-thu (thunderstorm and heavy rain). In the opposite case, when the standard deviation is zero, only one single value is represented which means that one individual only described the rain type in question. The rain in the little rain group (r) has slightly lower median durations (between 15 and 30 minutes) as well as smaller values of standard deviation

(3- 11 minutes) as compared to the heavy rain group (R). The heavy rain group has median values ranging from 25 to 75 minutes and the standard deviation takes values between 6 and 47 minutes. The standard deviation of the rain types with little rain is lower because the values are lower in general and thus the range of possible values becomes smaller as well.

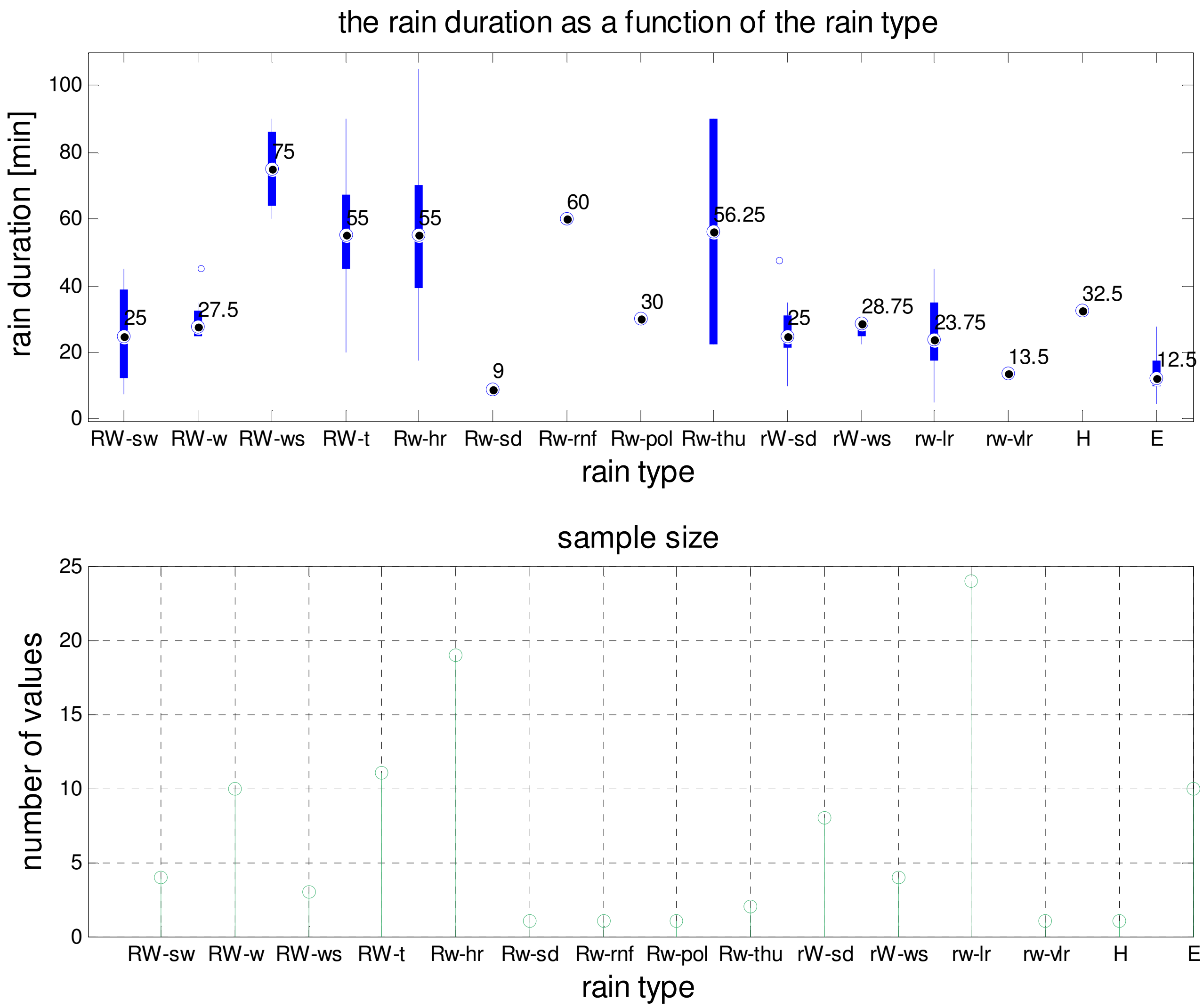

Figure 26The duration of the different rain types

The intensity of rain was more difficult to assess, because the rain height is not measured and thus the answers can't be expressed in millimeters. The intensity was described with words. Considering all the answers the following scale was defined:

Table 15-The intensity scale

very high	5
high	4
moderate/rather high	3
low	2
very low	1

The values from 1 to 5 are scores and don't have any units. The purpose of these values is to display the data on a graph. The value of the score increases as the intensity described increases. As expected, the heavy rain type classes R present larger values of intensity than the light rain type classes r. The values of the mean and the standard deviation for both groups are shown in the two tables below. The standard deviation is zero in the case when only one value is given (e.g only one person was describing a certain type of rain). An example is the short and intense rain (Rw-sd). Its average intensity is very high. The rain types heavy rain-strong wind (RW-ws), windstorm and heavy rain (Rw-sd), and heavy rain with runoff (Rw-rnf) also represent high mean values of scores (larger than or equal to 4). The rainfall intensity is high for these rain types. The extraordinary rain has also high rainfall intensity. The hail rain type has a moderate intensity. However, its strength is enough to endanger the harvest of beans. The light rain is situated in the categories low to very low intensity. The very low intensity is observed for the type: very light rain (rw-vlr).

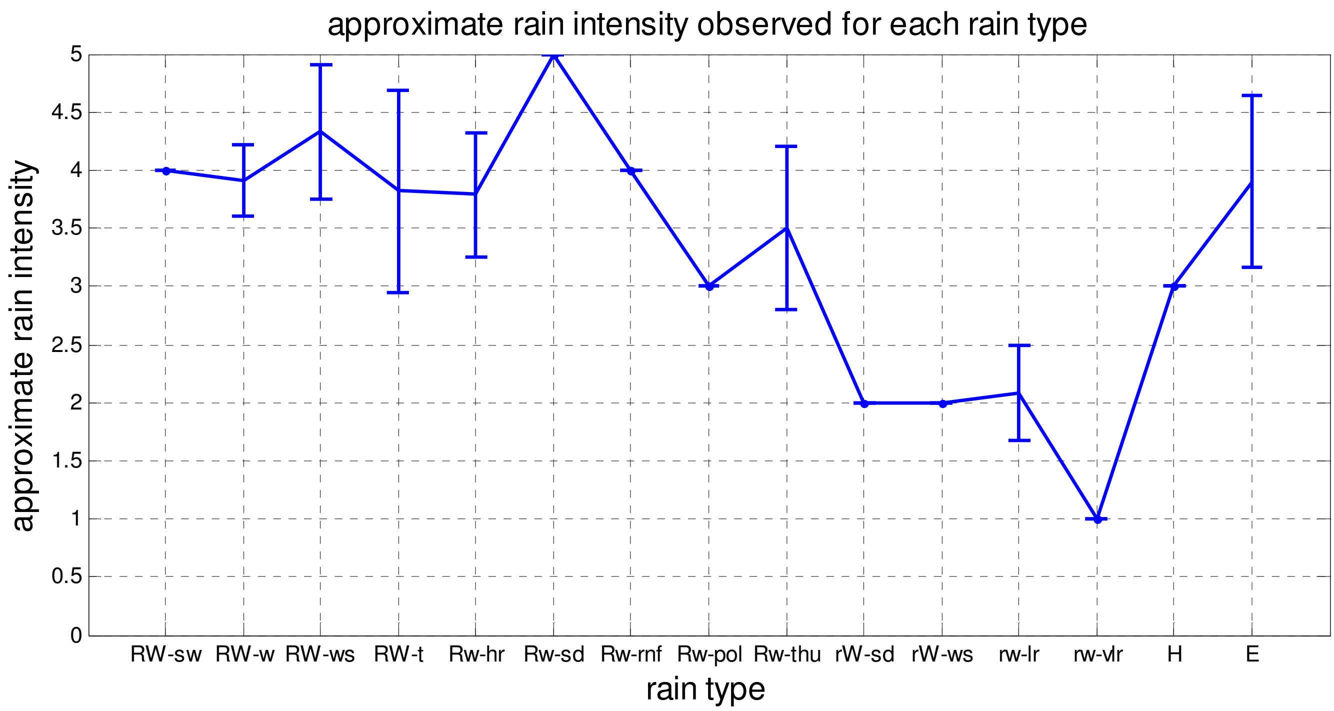

Figure 27-The intensity of the different rain types

Table 16- The intensity of the heavy rain types

Type: R	RW-sw'	'RW-w'	'RW-ws'	'RW-t'	'Rw-hr'	'Rw-sd'	'Rw-rnf'	'Rw-pol'	'Rw-thu'
average	4	3.91	4.33	3.82	3.79	5	4	3	3.50
standard deviation	0	0.30	0.58	0.87	0.54	0	0	0	0.71

Table 17- The intensity of the light and other rain types

Type: r,H and E	'rW-sd'	'rW-ws'	'rw-lr'	'rw-vlr'	'H'	'E'
average	2.08	1	2	2	3	3.90
standard deviation	0.41	0	0	0	0	0.74

The third part of the study is considering rain events which take place outside the rainy season. The villagers were asked if there are rain events outside of the rainy season. 93% agreed that they observed rain during the dry season. The two rain types identified were heavy rain (26.6%) and light rain (83.3%). The sum of the percentages doesn't give exactly 100%, because on one hand 16.6% affirmed that both types are possible and on the other hand 7 % do not think that rain is possible outside the rainy season. The months at which such rain is observed is January (30%), February (93%) and March (46%). The intensity of such rain is most often said to be low (76.6%) and sometimes high (26.6%). Nevertheless, the durations are very variable with a mean value of about 21 minutes. The graphs illustrating this data are given in the figure below.

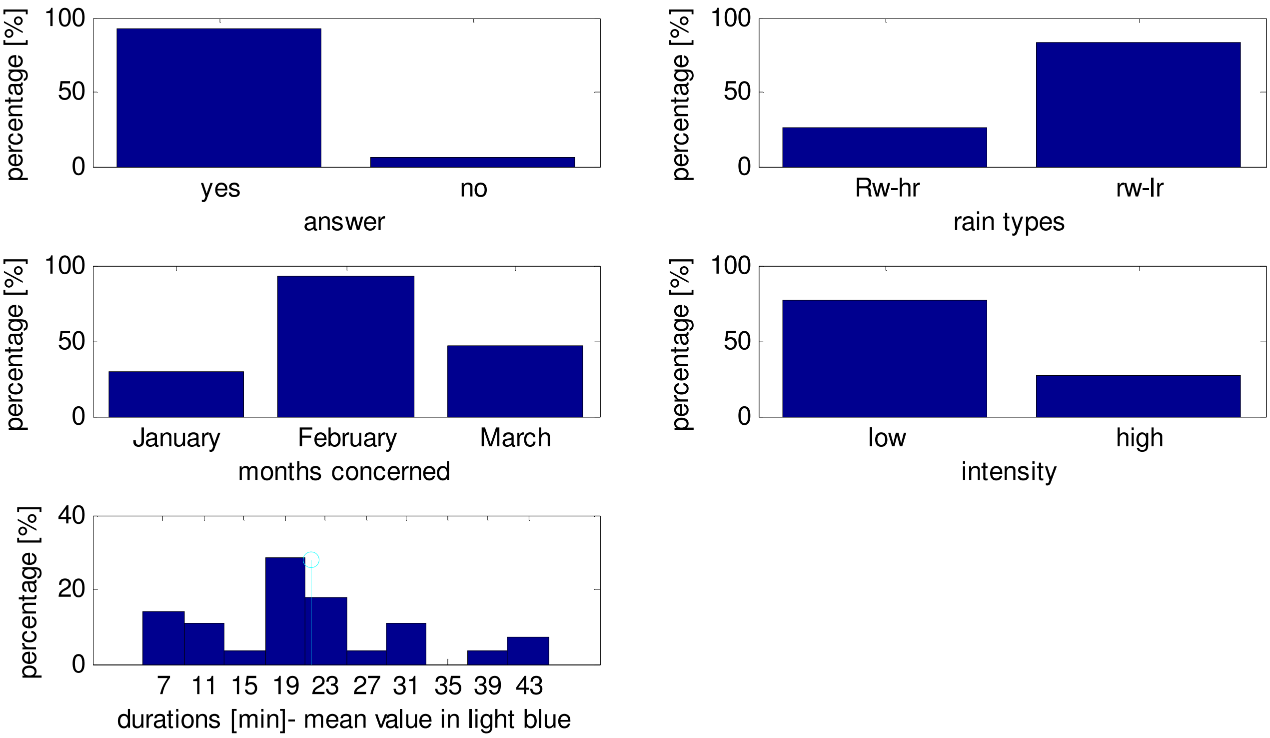

Figure 28-The events outside the rainy season

This gives a general impression of this phenomenon. In the following the events in recent years are considered. The farmers all agree that such events are rare. In the figure below, the fraction of the villager which observed a specified number of rain events during the dry season is shown. For all three years, a fifth of the individuals does not think that there was any rain at this period. The most common answer was that there was one such an event. Only in 2009 few farmers said, that there were three such events. For the other years the maximum is at 2. In the graphs are also always shown the values of the percentages.

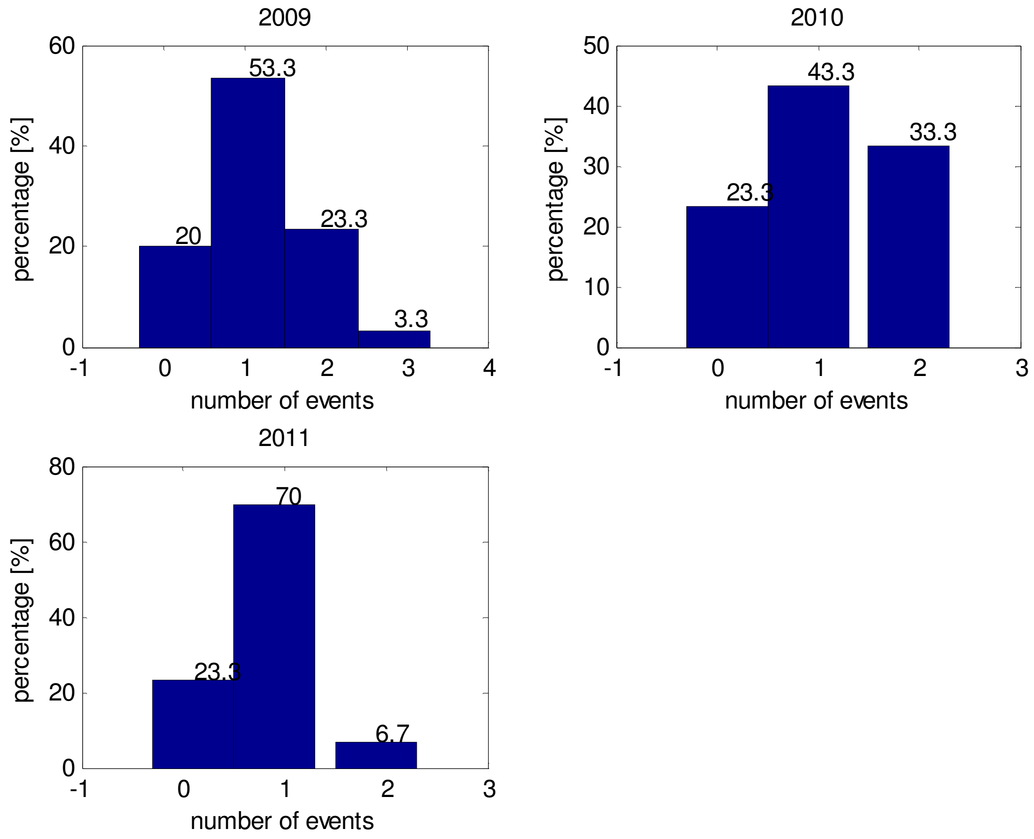

Figure 29- Number of events during the dry season for the year 2009, 2010 and 2011

The causes of such events were that God had brought this rain. Most villagers did not know how to answer this question. Particularly, here they didn't talk about the extraordinary rain, which is invoked by humans. It is difficult to explain this. One possible reason might be that the moment when such a particular rain is falling not all the natives from Tambarga are aware that it is such a type of rain.

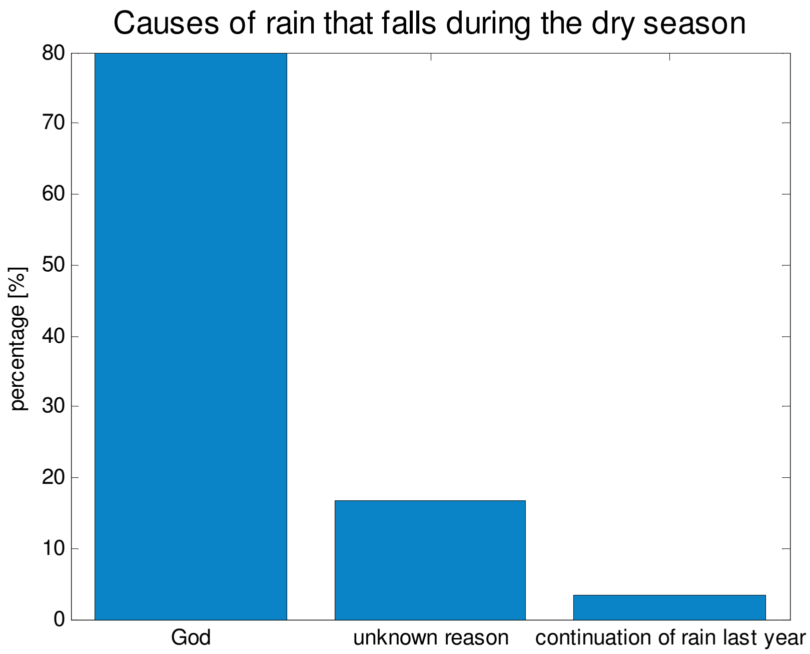

Figure 30- Causes of the rain events occurring during the dry season

One woman thinks that the rain is the continuation of the rain of last year (2011). The year 2011 was a very dry year. As it was raining one time during the dry season in February 2012, she thought this rain must be the one that was missing in the preceding rainy season. The rain falling during the dry season has many positive effects. Two third or the interrogated persons think that the rain is beneficial. 20% think that the negative consequences overweigh and only 13% think that they have both positive and negative effects. In the following figure on the left hand side this data is graphically presented.

In the table below are listed the possible positive and negative consequences, that might bring forth a rain outside the rainy season.

Table 18-The effects of rain occurring during the dry season

positive effects		negative effects	
1	Allows ripening of the fruits	a	They come together with the wind that destroys houses.
2	Brings some freshness	b	The ground is heating up, the heat is not comfortable for the villagers and the animals
3	Are good for the health of humans and animals	c	They provoke some diseases
4	The grass can regenerate	d	The grass is dirty and has a bad odor. The animals can't graze or get sick. Human health is also affected by it.
5	More food for ruminant animals	e	One cannot sow , because the amount of water is not enough.
6	The soil is wet		
7	The leaves of the baobab trees are growing (used to make a soup)		
8	They announce the beginning of the rainy season		

The graph on the right hand side of figure x, is showing the percentage of times, one of the effects of rain was mentioned during the interviews. The light colored bars represent beneficial effects of the rain and the darker bars represent negative answers. The most mentionned positive effects are that the grass can regenerate (category 4) , that the fruits are ripening (cat. 1), that the soil is wet (cat.6) and that it is fresher now (cat.1). An undesired effect is, that the grass gets bad with rain and that the risk that some diseases proliferate increase. The health of the farmers and their families is also at risk, if they eat the meat of a sick animal.The categories c and d are the consequences described here and are most commonly cited.

Particularly, one of the negative effects seems to be the complete opposite of one of the cited positive effects. The persons interviewed at the beginning, remembered well the rain that has fallen in February and appreciated the freshness it brought (category 1). Towards the end of the conduction of interviews, the interrogated farmers had rather a negative impression of that rain, because the ground seems to heat up even more (category b). Hence, considering these responses chronically, the freshness is only a short-term effect and on the long term the heat returns and is believed to be more pesant than before. The same villagers, who were mostly insisting on the negative effects of the rain during the dry period, claimed that the only positive effect was that the rain makes the leaves of the baobab tree grow, and the latter are used by the women to make a soup. On the graph, this answer falls in category 7.

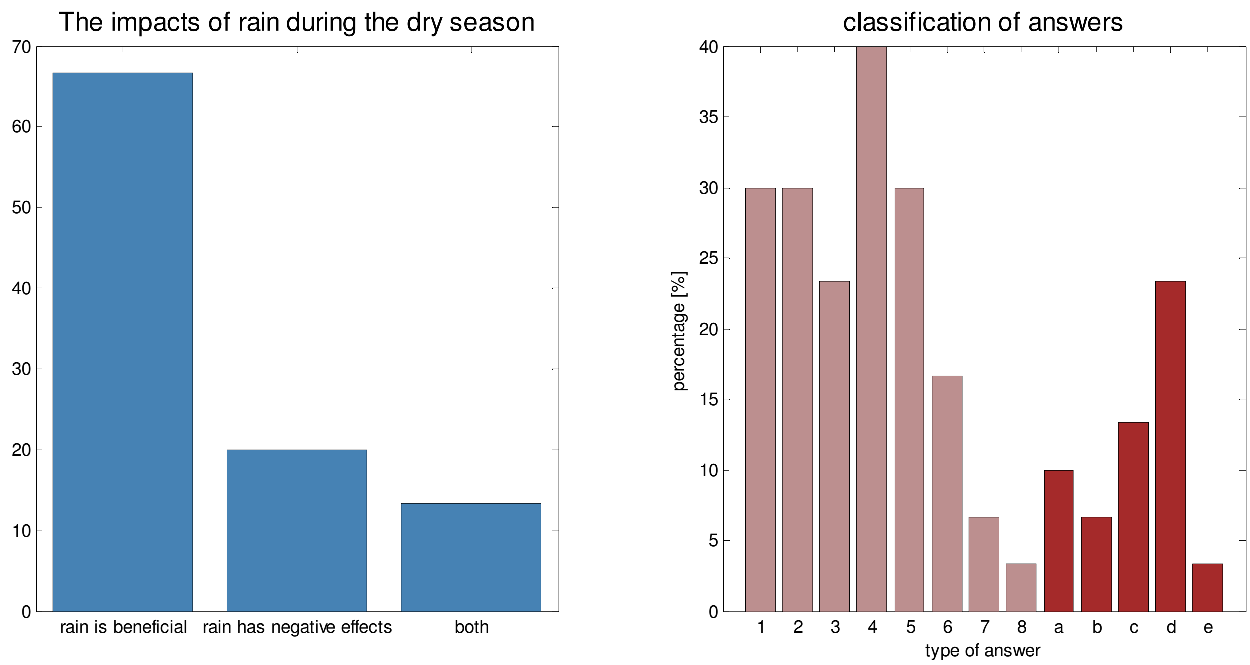

Figure 31 The impacts of rain during the dry season

In order to have a more detailed view of the rain events which occur unexpectedly during the dry period, the farmers were asked what they think about the rain that occurred this February 2012. In the table below are summarized the answers and allocated to categories.

Table 19- The effects of the rain in February 2012

positive effects		negative effects	
1	Soil is wet	a	The ground has heated up considerably
2	Grasses can regenerate	b	diseases
3	The leaves of the trees will grow which are used for a soup	c	The grass became dirty
4	It was moderate rain, it rained much more elsewhere	d	The animals cannot graze anymore
5	It was a small rain, which didn't have much effect		
6	Brought freshness-people slept well that night		
7	It was a good thing		
8	It was beneficial for animals and human health		
9	There was no wind.		
10	God sent this rain.		

This rain did not have a large effect. It only wetted the soil and brought some freshness. The problem was that the most amount of rain has fallen in another village not far from Tambarga. The positive and negative answers were arranged in a similar way as above. The fact that God brought this rain is neutral, but it was added to the positive group of answers. Less than 10 % of respondents talked about the negative effects of the rain, such as the heating of the ground and the diseases. The impact was not large.

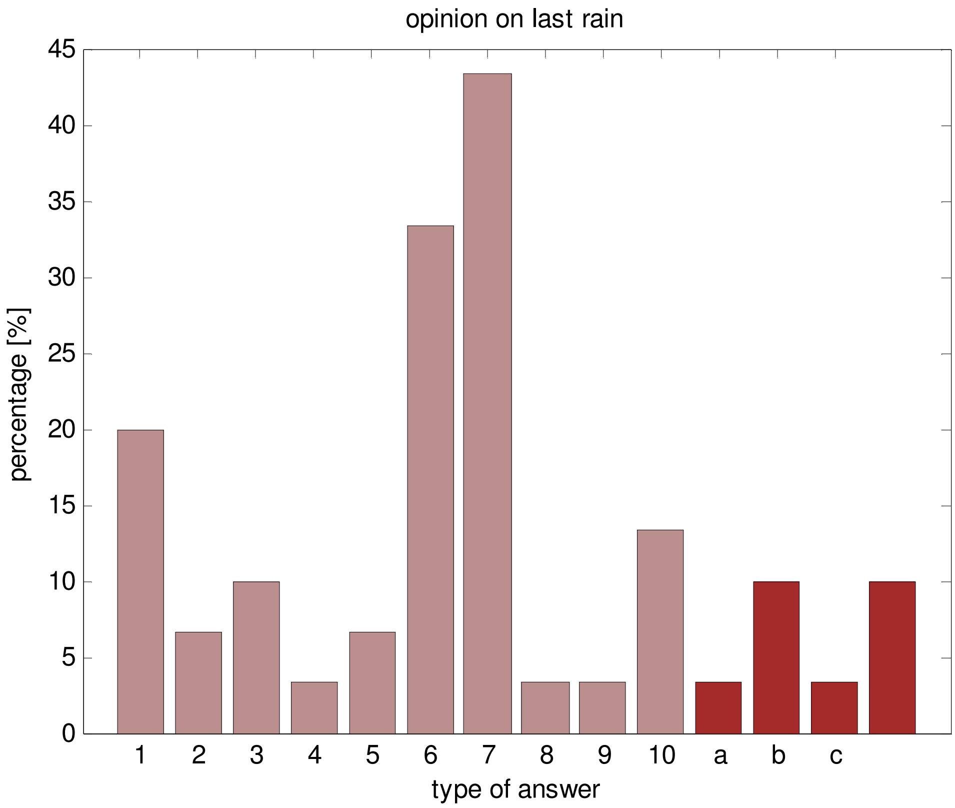

Figure 32-The effects of the rain in February 2012

4.5 Discussion

The decrease in rainfall had a large impact on the people of Tambarga and is thus a reoccurring element in this survey. Also the quantitative data, the curves displaying the number of rainy days show clearly the decreasing trend. Generally, the rainy season is expected to last from May to October, but additional to the concern about quantity, some people said that the start is shifted in time. Comparing the data of 2010, with the quantitative results is not possible for the length of the rainy season, because the data does not cover the whole period. However, according to the villagers the month of August is the month with the most rainy days. This is in agreement with the scientific data. The perception of changes in the rainy season can also be related to another study which considered the farmer's perception of climate change in the rural Sahel.[15] The observations of farmers in Senegal concerning changes in rainfall were that the rain amount and the rain intensity decreased, that the rainy season stops earlier, that the rainy season became shorter, that longer dry periods within the rainy season occurred and that the number of rainy days was diminishing. This observations are comparable to those of the villagers in Tambarga.

The second part of the study treated the question of the perception of rain. The rain can be described by different characteristics depending on the point of view of the observer. Even in a small village as Tambarga the answers differed accordingly. The rainfall in Tambarga is characterized by: the quantity of water which is falling, the regularity, the wind and the consequences of the rain. Not surprisingly, the amount of rain is an important criterion, because it has a direct effect on their livelihood and the decision they make about farming such as the appropriate time to seed. A certain amount of rain is necessary for the seeds to grow. Another important criterion is the regularity of the rain events in time. If the time period between two rain events is too large, the seeds die. Only about 3% of the individuals distinguished different types of rain events taking into account the direct consequences of the rain. Such observations include ponding of water on the surface, runoff in the river or even beyond. The third most mentioned criterion was wind. The wind sometimes accompanies rain and may destroy the houses they built, knock over trees and endanger the harvest. The observations may improve the rainfall forecasting. The intensity, the duration and the months concerned give some indications on the type of rain. However, it is difficult to relate the different rain types as described by the farmers to the scientific research.

The last part of this study, which is considering the rain of the dry season, gave some new insights. Especially, the paragraph dealing with the effects of rain shows that rain influences their lives in many ways. The domains covered by the respondents were human health (diseases and freshness), soil moisture (agricultural aspect), animals, leaves of trees, food (fruits and grass), their housing, temperature and wind. In a further study, the effect of rainfall during the rainy season may also be investigated. In particular, an interesting question would

[15] Mertz, Ole, Cheikh Mbow, Anette Reenberg, and Awa Diouf. “Farmers’ Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel.” *Environmental Management* 43, no. 5 (2009): 804–816.

be if rain can have negative effects if the intensity is very high. Also here, it is difficult to make a link to the scientific data. In 2010 the stations were active only in the month of March and one single event could be identified for this month and the intensity was low. About 79% of the villagers also observed at least one rain event during this month.

4.6 Conclusion

This survey gave an insight to the perception of rain by the inhabitants of Tambarga. The open questions had the advantage that the respondents could exactly explain their thoughts without restrictions. The answers were organized in different classes. This survey allows elaborating a survey with more selective and targeted questions. For instance, the section with the different rain types can be further investigated. Three aspects should be considered: the quantity of rain, the meteorological conditions in general (such as wind, temperature) before, during and after an event, the effects of the rain, and the observations on the sky (cloud formation, shape, coverage…). These aspects respond rather to scientific needs.

However, this information can then be used for rain forecast. The predictors of rain should include not only observations of the sky, but also the indicators on the ground. For instance, the behavior of certain animals (insects) changes before a rain event. The indigenous knowledge plays an important role in scientific rainfall forecasting.[16] The perception of rainfall and its variability by the local people guides the way the scientific rainfall forecast needs to be communicated. The communication is only efficient if people's point of view and their way of thinking are understood. Predicting rain helps the local people to adapt more easily to difficult situations like droughts, if they are informed a certain time before. A study already exists which describes how farmers of Burkina Faso predict rainfall. They concluded that integrating the scientific forecast is possible. They found also that farmers evaluate seasons in terms of types and time of rainfall. The differentiation of rainfall types brings some additional information, because the same amount of rainfall may not lead to the same

[16] Roncoli, C., K. Ingram., P. Kirshen, and C. Jost. 2001. "Integrating Indigenous and Scientific Rainfall Forecasting in Burkina Faso". IK Notes, n. 39, December.

agricultural outcome depending on the event (e.g thunderstorm or prolonged consistent rain).[17] The scientists however can only measure the quantities of rain.

Another field of study is the spatial and temporal variability of rainfall and what strategies are used to adapt to changing conditions. In this study the temporal variability was discussed in terms of irregularity of rain. This aspect could be further investigated.

To sum up, this survey covered a large range of topics and gives rather a general overview than detailed information on specific aspects. Further surveys may be conducted by which certain topics can be further developed depending on the objectives.

[17] Roncoli, C., K. Ingram., P. Kirshen, and C. Jost. 2001. "Integrating Indigenous and Scientific Rainfall Forecasting in Burkina Faso". IK Notes, n. 39, December.

5 Factors controlling rainfall

5.1 Introduction

In this section the conditions which lead to the development of storms are examined. The variables studied in detail are the soil moisture, the latent and sensible heat fluxes, and the rainfall height at the event considered as well as the rainfall height of the antecedent event. Using a multivariate statistic, the principle components analysis (PCA), the influence of these parameters on the initiation of storms was evaluated. If the conditions favorable to the triggering of storms were known, they could contribute to the prediction of storms.

5.2 Implications

Numerous studies investigated the influence of the land surface on the development of convective storms.[18] Namely, the soil moisture feedback is considered being a controlling factor of the initiation of storms. Taylor et al. (1997) suggested that the conditions on the land surface may induce anomalies of low-level moist static energy following mesoscale rainfall events (10 km scale).[19] These variations contribute to the formation of small convective cells within larger disturbances.

Eltahir (1998)[20] proposed a hypothesis which relates the soil moisture to the subsequent rainfall. Wet soil moisture conditions affect the surface albedo as well as the Bowen ratio. The surface albedo is the fraction of the incoming solar radiation which is reflected. As the water content in the soil increases, the fraction of radiation reflected decreases. The Bowen ratio is equal to the ratio between the sensible heat flux and the latent heat flux. The sensible heat flux becomes smaller with respect to the latent heat flux as the soil moisture increases. These effects, the decrease in surface albedo and the Bowen ratio, change the energy balance at the soil surface. The energy balance can be formulated as follows (Liang et al. 1994)[21]:

$$R_n = H_n + \rho_w L_e E + G + \Delta H_s$$

[18] E. A. B. Eltahir and J. S. Pal, “Relationship between surface conditions and subsequent rainfall in convective storms,” *J. Geophys. Res.*, vol. 101, no. D21, pp. PP. 26,237–26,245, Nov. 1996.

[19] C. M. Taylor, F. Saïd, and T. Lebel, “Interactions between the Land Surface and Mesoscale Rainfall Variability during HAPEX-Sahel,” *Monthly Weather Review*, vol. 125, no. 9, pp. 2211–2227, Sep. 1997.

[20] E. A. B. Eltahir, “A Soil Moisture–Rainfall Feedback Mechanism: 1. Theory and observations,” *Water Resour. Res.*, vol. 34, no. 4, p. P. 765, Apr. 1998.

[21] Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. 99(D17), 14415–-14428 (1994).

Where R_n is the net radiation, H_n is the sensible heat flux, $\rho_w L_e E$ is the latent heat flux, G the ground heat flux and ΔH_s is the change in energy storage.

The net incoming solar radiation is increased as the albedo decreases. Regarding the Bowen ratio, as the latent heat flux becomes more important, the land surface is cooling down when water changes phase (evaporation) and the water vapour content in the atmospheric boundary layer increases. The cooling of the surface enhances the net radiation that originates from the soil, which results in an increase of the total heat flux. The lower surface temperature implies also a lower sensible heat flux and a lower depth of the boundary layer. The two conjunct effects of higher total heat fluxes into the atmospheric boundary layer and the lowering of the extent of the latter provoke an increase in moist static energy magnitude and gradient. Therefore, the probability of rainfall as well as the amount of rain becomes larger. A recent study from Taylor et al. (2011)[22] showed that the probability of the development of storm is doubled in conditions at which large gradients of soil moisture occur (at length scales of about 10-40 km).

5.3 Objectives and method

The factors controlling rainfall are examined in this section with means of multivariate statistics, specifically principle component analysis. The objective is to analyze the importance of the soil moisture, the antecedent rainfall height, the sensible and latent heat flux for the different rainfall events identified in the rainy season of the year 2010. Additionally, this analysis may also support the classification of events or at least the regrouping of events with similar behaviour. The results of this analysis may be related with the analysis of persistence in the following section.

The variables considered here are related to each other. As explained above, the sensible and latent heat fluxes depend on the soil moisture state. The antecedent rain influences the soil moisture through infiltration of rainfall. In addition, the processes involved in the formation of storms are not the same if the meterorological conditions and topography change. Particularly, they depend on the type of land cover. On a dry sandy soil with sparse vegetation the soil moisture is less conserved than in soil with a protecting vegetation cover. The problem is that the soil moisture-rainfall feedback is observed at a scale of at least 10 km. The catchment of the Singou is smaller. Therefore, the relationship of the variables cannot be determined.

[22] C. M. Taylor, A. Gounou, F. Guichard, P. P. Harris, R. J. Ellis, F. Couvreux, and M. De Kauwe, "Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns," *Nature Geoscience*, vol. 4, no. 7, pp. 430–433, Jun. 2011.

5.4 Treatment of data

The principal component analysis is a multivariate statistic method. Different characteristics of an individual, which are measured simultaneously, are considered. The variables included in the analysis are the following:

1) rainfall height at the event [mm]

2) soil moisture [%]: The hourly soil moisture at 5 cm depth was calculated and its average value is computed over the 24h time-period preceding the rain event.

3) rain height of the antecedent event [mm].

4) the latent heat and 5) the sensible heat [W/m^2]: The sum of each of the heat fluxes is calculated over a 24h time period before the first rain was measured. The rain events 1, 2, 3, 28, 29, 30 were excluded from the analysis, because the data on the sensible and latent heat fluxes was not available at the corresponding dates.

The stations 1007, 1009 (hill), 1015 and 1016 were chosen for this analysis. Only stations which measure rainfall and soil moisture at the same time could be used, therefore stations, however reliable regarding the rainfall data, were excluded. The selection was made considering the data available at each station at the time of the rain events considered. The stations 1001 and 1010 didn't cover the whole time period for the soil moisture data.

For each of the selected stations the 5 variables explained above were computed. The variables and the individuals can be reassembled in a table. For instance the first three rows of the table of station 1009 look like this:

event nr.	antecedent rain [mm]	rain [mm]	latent heat [W/m^2]	sensible heat [W/m^2]	soil moisture [%]
4	0.762	3.556	6704.44	2381.08	2.93
5	3.556	1.778	5586.31	2445.45	2.96
7	5.08	0.762	5000.19	2385.29	3.03

5.5 Theory

The mathermatical explanation and formulas presented in this section are based on Morgenthaler (2007)[23]. In general, a multivariate data table contains p variables (columns) and n individuals (rows which represent single rain events). The corresponding matrix is in the following named Y. The geometric presentation of this matrix would be a cloud of n data points in a p-dimensional space.

A statistical multivariate method should apprehend all structures of the cloud consisting of these n points. The projection of the points is the fundamental method of multivariate statistics. Let v be the vector that generates a 1D-space and whose length is equal to 1. Then the projection of a point is calculated by the scalar product $y^T v$. Consequently, considering multivariate data, the projection consists of determining linear combinations of the original variables. These linear combinations are named components. A method to reduce the dimension of a multivariable dataset is to seek components, such that the original data structure is preserved by the most important component (or by the two or three most important components).

In principal components analysis, the objective is to create a system of components, sorted by decreasing order of importance. The aim is to find components which could replace the whole data set. The first component should represent the structure of the data as good as possible.

In other words, the objective can be formulated as follows:

"We are looking for a 1D space generated by a vector v of length 1 by which the projected observations have maximum variance. Thus, the component, we are looking for is given by:

$comp_1 = v_{11} (var_1-m_1) + ... +v_{p1}(var_p-m_p)$ which has maximum variance

s.t. $v_{11}^2 + ..+ v_{p1}^2 = 1$"

The variance of the component is: $Var (v_{11}Y_1+ v_{p1}Y_p) = v_1^T \sum v_1$

[23] Morgenthaler, Stephan. *Introduction à la statistique*. PPUR presses polytechniques, 2007.

where $\sum$ is the covariance matrix of the random vector Y and is nonnegative. It is defined by:

$\sum = \Omega\Lambda\Omega^T$

- Ω is an orthogonal matrix and its columns correspond to the eigenvectors of the matrix $\sum$
- Λ is an orthogonal matrix with the diagonal elements $\lambda_1 \geq \lambda_2 \geq \ ... \geq \lambda_p \geq 0$

For any unit vector, the following inequality is true:

$v^T \sum v = v^T \Omega \Lambda \Omega^T v = a^T \Lambda a$ with $a = \Omega^T v$

$a^T \Lambda a = \sum_{j=1}^{p} a_j{}^2 \lambda_j \leq \lambda_1 \sum_{j=1}^{p} a_j{}^2 \leq \lambda_1$

If we choose v equal to the first column of Ω (v_1), then we have:

$v^T \sum v = v_1{}^T \Omega \Lambda \Omega^T v_1 = \lambda_1 \geq v^T \sum v$ (for all v)

The solution of the optimization problem is to choose v1 equal to the eigenvector of $\sum$ whose largest value is λ_1. Moreover, the largest value of the variance Var ($v_{11}Y_1 + ... + v_{p1}Y_p$) is λ_1.

Actually, the matrix $\sum$ is unknown and has to be replaced by the covariance matrix S. This matrix is also symmetric and nonnegative: $S = VLV^T$

The columns of V are the unit eigenvectors of S and L is the diagonal with elements $l_1 \geq l_2 \geq ... l_p \geq 0$, the eigenvalues of S. The first principal component is determined using the first column of V. This eigenvector has the largest eigenvalue (l_1) of S, which is equal to the estimated variance of the component. Var ($comp_1$) = Var ($v_{11}(var_1 - m_1) + ... + vp_1 (var_p - m_p)$) $= l_1$

As the units of the variables are not compatible, they are standardized:

$\frac{var_j - m_j}{s_j}$ where j = 1,…,p

The covariance matrix of the standardized values is the correlation matrix R of the original variables. The sum of all the eigenvalues of S is equal to the trace of S and is noted: $\sum_{j=1}^{p} s_{jj}$. The fraction of the maximum eigenvalue of R represents the part of the variance explained by the first principal component. The second principal component is determined by the second eigenvector for which the second largest eigenvalue was found. The fraction of the variance explained by both components is the ratio of the sum of both eigenvalues divided by the trace of S = the variance over all the variables. The importance of a component is somehow measured by the value of its eigenvalue.

The first two principal components can be represented in a biplot. The biplot is representing the p variables in only 2 dimensions. The second component is plotted as a function of the first principal component. The scores of each observation is calculated and plotted as a point on the graph. Isolated groups of points on the resulting graph show individuals which have a different behavior. The weight in each component of each variable is represented as a vector. The component score for a variable i is: $c_i = v_i$. The points which are situated close to such a vector have unusually large values for these variables. Likewise, if they are situated in the opposite direction, they represent considerably small values for this variable.

5.6 Results

The graphs presented below are showing the results of the Multivariate Analysis for each station. Some events had to be excluded because of unavailable data. In the case of station 1007, event 7 was excluded, for station 1009 event 6 and 41, for station 1015 events 47, 48 and 49, and for station 1016, event 42. That is the reason why for none of the stations all the events could be presented. However, together they are presenting all the data. The comparison of the graphs is not straightforward, because the components maximizing the variance calculated are different at each station. The direction of the variables is also slightly different on each graph, but the arrangement and their respective directions are similar. Generally, the variables soil moisture and antecedent rain are in the upper left quadrant, the variables latent heat and rain in the upper right quadrant and the variable sensible heat in the bottom right quadrant. The variable antecedent rain for station 1015 is also in the upper right quadrant, but its direction is still mostly vertical, which is observed for the other stations too.

It is expected that the results of the stations are not exactly the same. Depending on local conditions (i.e. in the intermediate vicinity of the stations), the measured variable may exhibit slightly different behaviors. Therefore, the fluxes measured and the soil moisture varies correspondingly. The largest differences are expected between station 1009 which is situated uphill and the other stations. Stations 1007 and 1006 are not placed far from each other. Station 1015 is the one with the shortest distance to station 1009; however its location is much closer to the other stations.

In order to better visualize certain resemblances or differences in the point patterns of the distribution of individuals, circles were drawn around groups of points. The grouping of the points was carried out in a qualitative manner; since the points are not always clustering exactly the same way. Points which are often in proximity of other points are added to the group. The colors are used to better distinguish between the groups and to easily compare the same group on the other graphs. Not only groups, but also some isolated points are encircled. Obviously, the point patterns are similar whatever station considered. This resemblance can be explained by the fact that the scale of the field of study is smaller than 2 kilometers here, and the local conditions are comparable for all locations. Hence, this is a good result in terms of accuracy of the data measurements. The rain events are represented by the individual points on the biplot and their positions relative to the variables can in some cases reveal information of the factors explaining the event.

Two groups of clusters can be clearly identified on all the graphs, the ones in the violet (events 4,5,6 and 7) and dark blue circles (35, 36, 37 and 38). These groups exhibit a special behavior and are different from other events. The other groups are not always well aggregated groups and the some observations are not always at the same location relative to the others. They can therefore not be identified as clusters. Moreover, they are situated close to the center of the graph and cannot be related to any variable.

The violet group includes the earliest events considered in this analysis (events 1-3 were excluded). The conditions are relatively dry at the beginning of the rainy season. The events of this cluster are possibly influenced by the magnitude of the sensible heat. The latent heat is less important as the soil moisture is low and the evaporation is not important yet.

The blue group comprises event which are at the opposite side of the variables rain and latent heat. These events are observed when low latent heat fluxes occur.

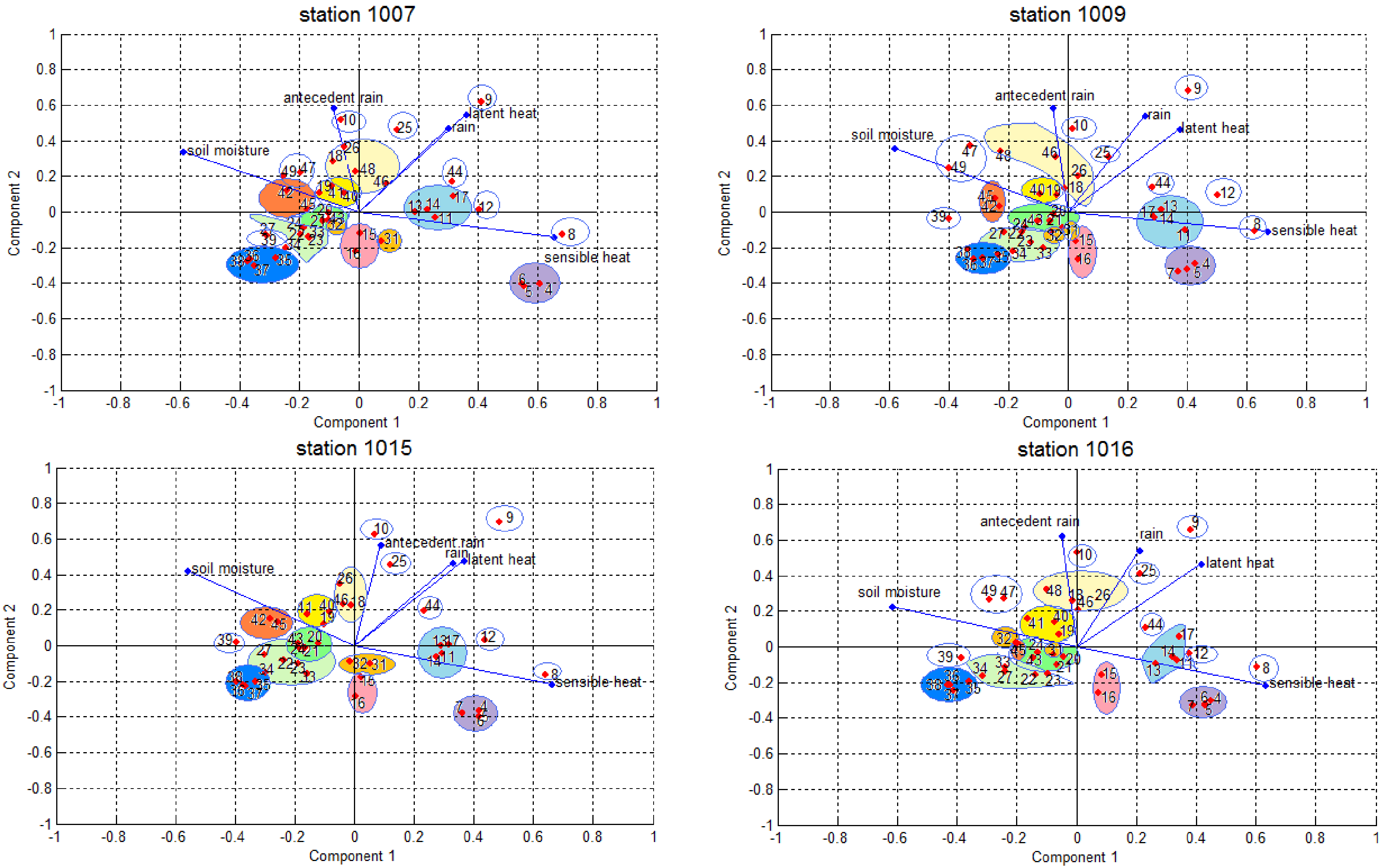

Figure 33-The graphs of the principle components analysis for the 4 stations selected

To analyze the behavior of the different events, the graph of station 1007 is studied in further detail. As for event 8 can be said that it is influenced by the sensible heat flux and is most possibly occurring if the variable sensible heat is important. Similarly, if latent heat and the rainfall height at the event are important, the event 9 is likely to occur. Particularly, a cluster of events is appearing at the opposite side of the graph in the bottom left quadrant. These events are also influenced by the two parameters rain and latent heat, but they are more conditioned by lower values of latent heat. This cluster can also be identified in the upper graphs for the other stations; it corresponds to the groups with green, light green and dark blue color merged together. In the figure below, the cluster is the one contained in the small ellipse. Only one single event, event 10 was presenting rather a high score for the variable antecedent rain. In the case of soil moisture, no sensitivity of any event could be detected. Events which are situated close to the center of the biplot, cannot be related to a variable.

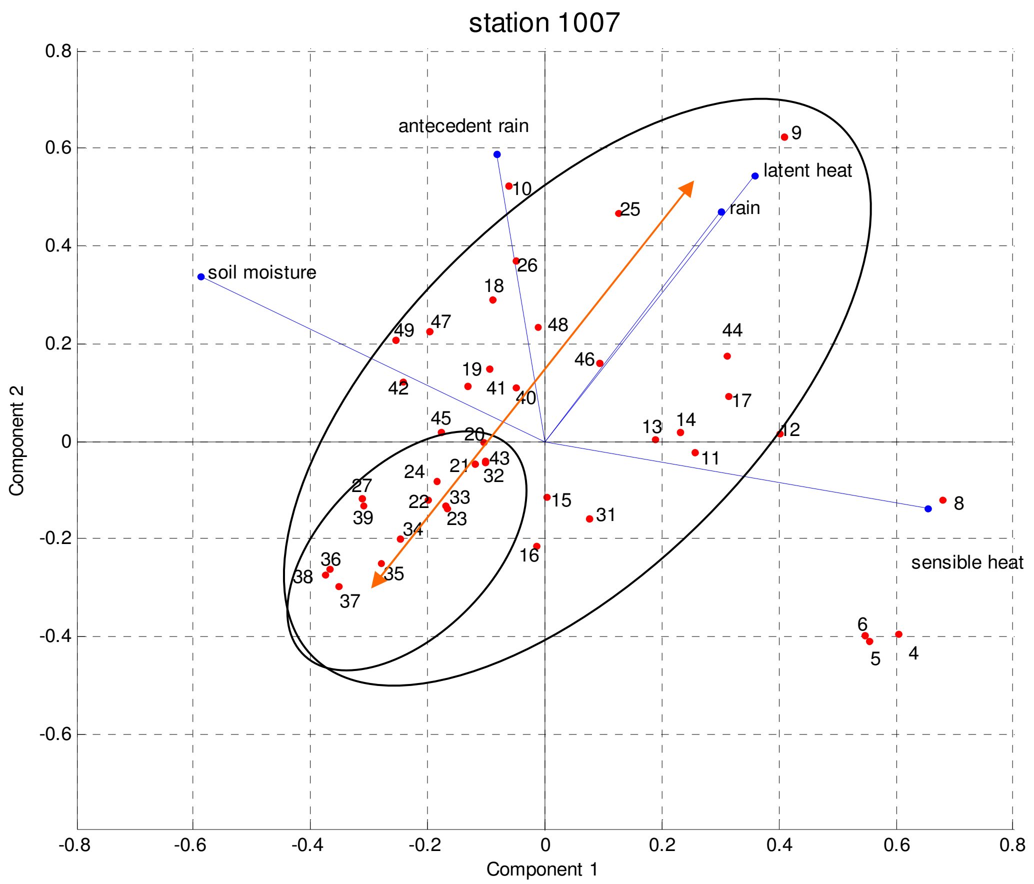

Figure 34 The results of the principle components analysis for station 1007

On this graph two main directions can be identified. The events which are strongly influenced by the variable latent heat. As already said, the individuals can be influenced in two ways, either if the variable has a high importance at the event considered or if the importance of the variable is very low. However, only these two main directions can identified on this plot. The plots for the other stations show a more dispersed pattern. Thus, this cannot be generalized. Nevertheless, the event 9 is everywhere at the extremity of the vectors of rain and latent heat, and also the large cluster in the opposite direction appears on each graph. The group with events 4, 5, 6 and 7 have different characteristics from all the other events. They are probably favoured for low soil moisture conditions. This events occur at the beginning of the rainy season where the frequency and magnitude of rainfall is low and the soil is dry.

5.7 Conclusion

In conclusion, only single event can be attributed to the variables sensible heat (event 8), latent heat and rain (event 9) and antecedent rain (event 10). Regarding soil moisture no event was clearly identified as to be most probable to occure when the soil moisture is close to saturation. However, a cluster of events (4, 5, 6, 7), which probably occur in the case when the soil moisture is very low, is appearing. They are observed at the beginning of the season under dry conditions.

The analysis here has some limitations due to the small scale of the field of study. The processes studied here are of larger scale and the local variability of the controlling factors of rain may hide certain relations. However, comparing the data of the 4 stations allows to generalize certain observations. The observations of one station confirm the observations of the others, in the case when similar distributions are observed. In the opposite case, the differences are due to local variations. The similarity between the stations reveal a certain pattern of different types of rain events specific to the basin of the Singou river.

Conclusions can be drawn from the graphs only for points which are at extreme edges of the graph or for clearly identifiable clusters. For all the other events, which are situated closer to the center of the graph, no special behavior can be attributed.

The events highlighted here can be compared to the events in the analysis of Persistence which is presented in the following section.

6 Analysis of Persistence

6.1 Implications

A villager in Tambarga told me: « Rain falls where it has already fallen ». This statement goes with the theory that a positive feedback of the soil surface to rain exists. It was pointed out in the previous section that knowledge on rainfall is crucial for the farmers. The rain in the Sahel has a high spatial variability. Therefore, knowing where rain is most probable enables the farmers to concentrate their efforts on the fields that are most probable to receive enough rain. The persistence of rainfall convective-scale rainfall patterns was analyzed statistically by Taylor and Lebel (1997)[24].

Their hypothesis is based on the positive feedback of the land surface. They pointed out that especially the vegetation can modify precipitation. This influence had been shown by mesoscale and large-scale studies. In semiarid climates the soil moisture is the limiting factor which the evapotranspiration rate depends on. Hence, the antecedent rainfall indirectly influences the PBL. Dynamical effects or changes in stability of the lower atmosphere to moist convection may have an effect on subsequent rain. Hence, the positive feedback of rainfall is possible, if the conditions are favorable.

Furthermore, it is generally believed that variations in soil moisture influence the PBL in two ways: Firstly, the heterogenic soil moisture pattern induces variability in the PBL which leads to formation of zones where convection is favored. Nevertheless, this effect is attenuated at a local scale (of a few kilometers), by advection and turbulence processes. Secondly, the soil moisture variability can bring forth mesoscale flows in the PBL. These flows may lead to convergence which is necessary for convection to take place.

6.2 Questions

Taylor et al. considered in their analysis the spatial variability of rainfall (e.g. the rainfall pattern) by calculating the differences between each pair of rain gauges. The number of pairs of rain gauges equals the number of combinations of rain gauges possible.

Two different types of persistence were defined:

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[24] Taylor, Christopher M., et Thierry Lebel. 1998. « Observational Evidence of Persistent Convective-Scale Rainfall Patterns ». *Monthly Weather Review* 126 (6) (juin): 1597-1607. doi:10.1175/1520-0493(1998)126<1597:OEOPCS>2.0.CO;2.

I) Short-term persistence

Evaporation is influenced by the previous rain that has fallen. The drying of the top soil layer lasts approximately 1 to 2 days. During this time the evaporation is mostly influenced by the water that fell at the antecedant event. The persistence is determined by comparing the rainfall pattern of the rain that fell the last 2 days to the rainfall pattern for the day under consideration.

II) Long-term persistence

The evaporation rates are also influenced by the reservoirs in the deeper soil and leaf development. If the top soil is dry, the influence of these two parameters is high. The persistence here is evaluated by analyzing the relationship between the rainfall pattern of the rainfall accumulation over the previous 10 days to the daily rainfall.

In the feedback model mainly two relations were considered being responsible for persistence in rainfall patterns: the sensitivity of evaporation to rainfall and the seinsitivity of rainfall to surface evaporation. However, the evaporation is not the only driver of surface convection, other factors such as atmosphere stability and humidity also influence the development of a storm. Taylor et al. found that the feedback is therefore more likely in deeper, more intense storms[25].

The same analysis is applied here on the dataset of the Singou river catchment. There are differences to the study carried out by Taylor et al. concerning the area and the period of study. In their paper they mentioned a network composed of approximately 100 rain gauges which are separaterd by 7.5 - 15 km from each other. The data used comprised 4 years of observations. By contrast in this analysis, the maximal number of rain gauges used is 10 which are separated at maximum by a distance of 2.5 km and the time period covered is 4 months only. As the objective was to observe the variability of mesoscale convective systems, the results may differ in this smaller geographical context of the study here.

6.3 Method

Taylor et al. studied short-lived persistence using daily rainfall data. In this thesis, the focus is on singular rain events, so the analysis of persistence can be reformulated. The influence of

[25] Taylor, Christopher M., et Thierry Lebel. 1998. « Observational Evidence of Persistent Convective-Scale Rainfall Patterns ». *Monthly Weather Review* 126 (6) (juin): 1597-1607. doi:10.1175/1520-0493(1998)126<1597:OEOPCS>2.0.CO;2.

the antecedent event on the subsequent event is estimated instead of the influence of the two preceding days. Certain events are separated by a dry period of more than 2 days. In such a case, evaporation (due to bare soil drying) will not be the only factor influencing the initiation of the rain event.

The cumulative rainfall for an event measured by each station is considered. The interesting variable is not the amount of rain, but the variability of rain at different locations, thus the differences between each pairs of rain gauges are calculated. All the combinations of rain gauges are included. If for instance, the data from ten different rain gauges were retained for an event, the differences were calculated for the 45 (10 + 9+…+2+1) possible combinations. As a result, for each event 45 values of differences were obtained. The comparison of these differences for two distinct events is made by regression analysis.

In the case of long-term persistence, the 10-days accumulation of rainfall preceding an event is calculated. In the same way as above the differences between the rain gauges are calculated and compared to the differences of the cumulative rainfall for the event in question. In the following paragraph the linear regression analysis is described in more detail.

In the analysis several criteria were adopted:

1. The rainfall height at the day considered must be larger than a certain threshold value. In the paper the threshold was applied to the variable daily rainfall, whereas in the analysis here the event rainfall is considered. Different threshold values are applied.

2. The stations situated at a distance of 5 km must measure rainfall larger than half of the threshold value. As for the study area here, all the stations are always included in this radius. This means that all the stations must satisfy this criteria.

3. This criterion is adopted to avoid oversampling. The constraint consists of a minimum distance between two pairs of rain gauges which measure different antecedent rainfall differences. They used 5 km as minimum distance. This criterion can't be adopted for the Singou river basin, because this would exclude all pairs of rain gauges. Thus, in the interpretation of the results the possibility of oversampling must be taken into account.

The Criteria 4 and 5 explained in Taylors paper are constraints on time. As in the rainy season the events succeeds one close after the other, these constraints are far too restrictive. Instead of using a criteria by which events are excluded, the results are related to the parameter number of dry days preceeding the event under consideration.

In the second part of the analysis, the long-term persistence is considered. In the article using this method, the criteria was adopted that the comparison is only carried out when the last 2 days before the event, no rain was observed. For the data considered here, this is not possible because during the period considered (May to August 2010), a dry period between two events exceeding 2 days is very rare.

Two different analyses were carried out. The first analysis included the data of all the selected stations whithout restrictions. Different threshold values were applied in order to evaluate the influence of rain quantity on persistence. In the second analysis, data from all the stations was used. The differences between the stations situated on the hill and those in the valley were analyzed. In both analysis the short-lived and the long-term persistence were analyzed.

6.4 Theory: linear regression and significance

The statistic explanations and formulas presented in this section are based on Morgenthaler (2007)[26].

The statistic model of simple linear regression is: $y_i = \mu_i + \epsilon_i = \alpha + \beta x_i + \epsilon_i$

where :

-x_i: explanatory variable

-y_i: response variable

- α and β are constants

- ϵ_i represents error for the i-th measurement. The errors are non correlated realizations of a random variable with zero expectance and a variance of σ^2.

26 Morgenthaler, Stephan. 2007. *Introduction à la statistique*. PPUR presses polytechniques.

The constants α and β are estimated minimizing the squared error for all observations:

$C(\alpha, \beta) = (y_1 - \alpha - \beta x_1)^2 + \ldots + (y_n - \alpha - \beta x_n)^2$

Coefficient of determination: $R^2 = \frac{(SST - SSE)}{SST}$

where:

$SST = (y_1 - \bar{y})^2 + \cdots + (y_n - \bar{y})^2$ (total sum of squares) = SSM (model) + SSE

$SSE = (y_1 - \hat{y}_1)^2 + \cdots + (y_n - \hat{y}_n)^2$ (sum of squared errors)

The coefficient of determination is the degree by which the variation in y is affected by x. R^2 can take values between 0 and 1.

To assess the significance in regression analysis the F statistics is used:

$F_{obs} = SSM / SSE$

Where $SSM = (\hat{y}_1 - \bar{y})^2 + \cdots + (\hat{y}_n - \bar{y})^2$

F measures the importance of the slope of the regression curve. It represents the ratio of the mean square of the model (regression) to the mean square of the error. The null hypothesis in this test is that the explanatory variables are not adequate to describe the response variable y. For large values of F, this hypothesis is rejected. The value of F is compared to the quantile F_{obs}.

To determine the significance of the correlation coefficient the p-value associated with this test is calculated. The p value represents the probability that the F value is more extreme F_{obs} under H_o. The p-value of a test is high if F_{obs} is close to the center of the distribution, and is small if it is situated at the extreme parts of the distribution. Extreme values are less likely to be observed and thus the significance increases as the p-value decreases. As a rule, it is often assumed that the null-hypothesis is rejected when the p-value is smaller than 5 %.

The zero-hypothesis that the slope takes the value of zero is tested. The hypothesis is rejected if the observed value is larger than $qF_{1,\ n-2}$ (95%). The latter corresponds to the 95% quantile of the F law with 1 and n-2 degrees of freedom. n is the number of measures. The value of alpha= 5% was used.

6.5 Results

a. Quantity of rain

The following graph shows the evolution of the number comparisons possible for a given threshold on the rain amount (cf. criteria 1 and 2)

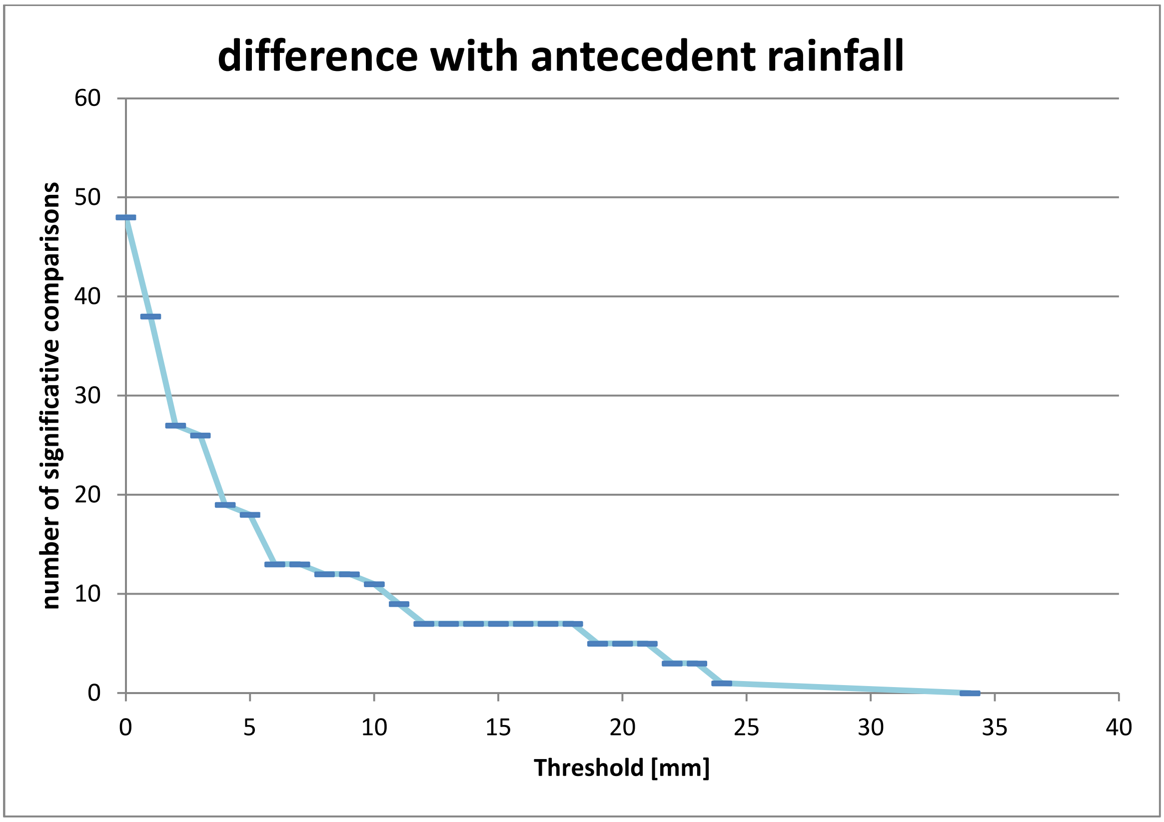

Figure 35- The number of comparisons as a function of the threshold applied on the cumulative rainfall per event

For lower thresholds the decrease in the number of comparisons is very sharp. Then, for thresholds above 10 mm for several values no change is observed. The decrease is generally much slower. Also the number of comparisons retained at this level is much lower. There is an isolated group of high quantity rain events which is conserved till the threshold of 19 mm. In the following the influence of the rain amount measured on the comparisons is evaluated.

I. Short-term persistence

The figure below is showing the case when no threshold is applied. The R coefficient, which is shown on the x-axis results from the comparison of the rain gauge differences of the event to its antecedent event. The values of the minimum, average and maximum rain quantity (considering all the stations) at an event is shown as a function of the correlation coefficient of the 48 event comparisons. On the same graph the corresponding p-value is also displayed. The scale of the p-value is on the right hand side of the graph.

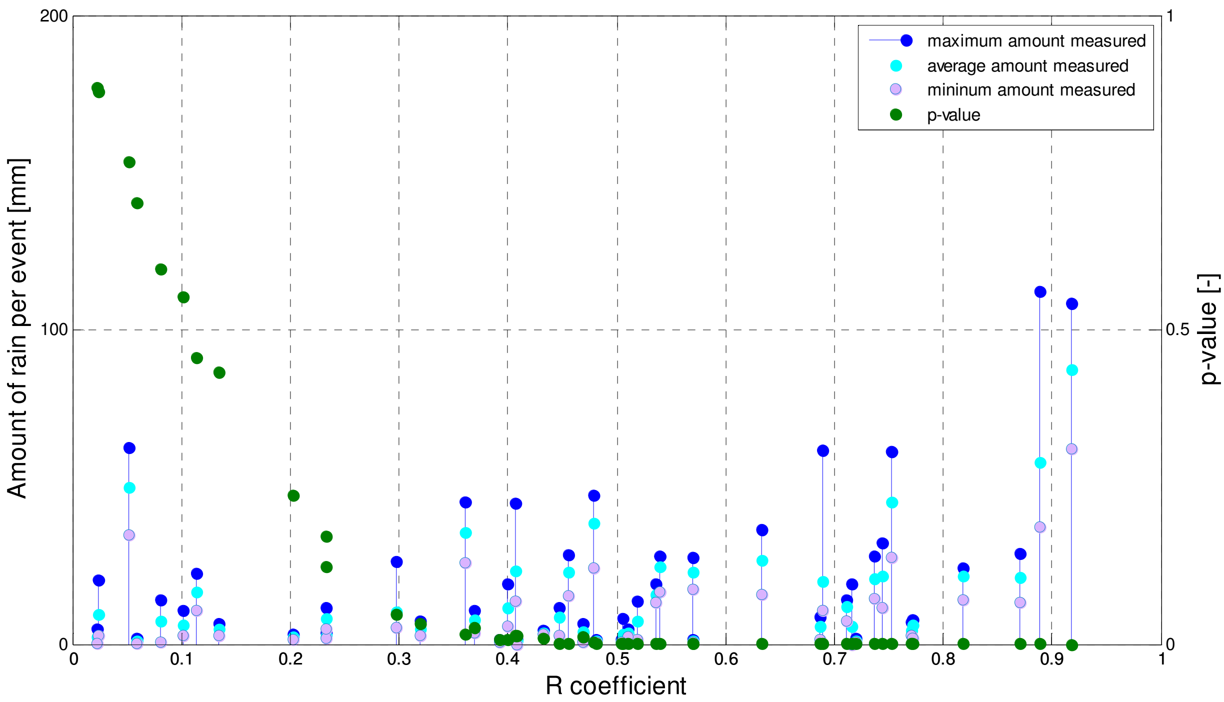

Figure 36-The influence of the amount of rain measured

The p value decreases as the correlation coefficient increases. Only the comparisons with a correlation coefficient higher than 0.35, are significant. The comparisons are considered which are on the right hand side with R coefficient higher as 0.35. There may be a trend of increasing correlation with increasing quantity of rain. However, this cannot be shown statistically, because the number of events is too small.

If the threshold on the amount of rain is increased, certain stations are excluded from the analysis. Depending on the event, different thresholds yield to the exclusion of stations. The R coefficient is also affected by the reduction of data used. In some cases the correlation is increased by exclusion of certain data and in other cases the contrary is observed. However, as the number of stations decreases, at a certain point the correlation coefficient becomes smaller as well. A graphic illustrating this, is added in the appendix.

The graph below is showing the evolution of the correlation coefficient throughout the rainy season. The correlation coefficient comparing the variability of the antecedent event with the one of the actual event is plotted in the upper graph at the date of the actual event. The bar plot below is showing the same data, but the bars are a function of the event number (regular spacing) instead of the dates. Additionally, the p-value is shown. Colors in both graphs indicate if the correlation is positive (blue) or negative (green). In certain cases, the p-value is very high (event 6, 10, 21, 30, 34, 36, 37 and 49), which means low significance. The associated correlation coefficients are rather small. Events with a high correlation coefficient ($R > 0.7$) are: 3, 9, 12, 14, 25, 28, 32, 38, 39, 41, 44, 46. The comparisons associated with these coefficients showed a positive correlation. In general, negative correlation is less frequent and the associated magnitudes are small to moderate. In the early season negative correlation is more frequent (events 2, 7, 11, 15, 16 and 29). In the month of August (events 30 – 49) many events are positively correlated with each other and the magnitude of correlation is rather high. There are three exceptions for which the significance was rather low. The frequency of events is also higher for the month of August. In May 8 rain events were identified, in June 8 events, in July 13 events and in August 20 rain events.

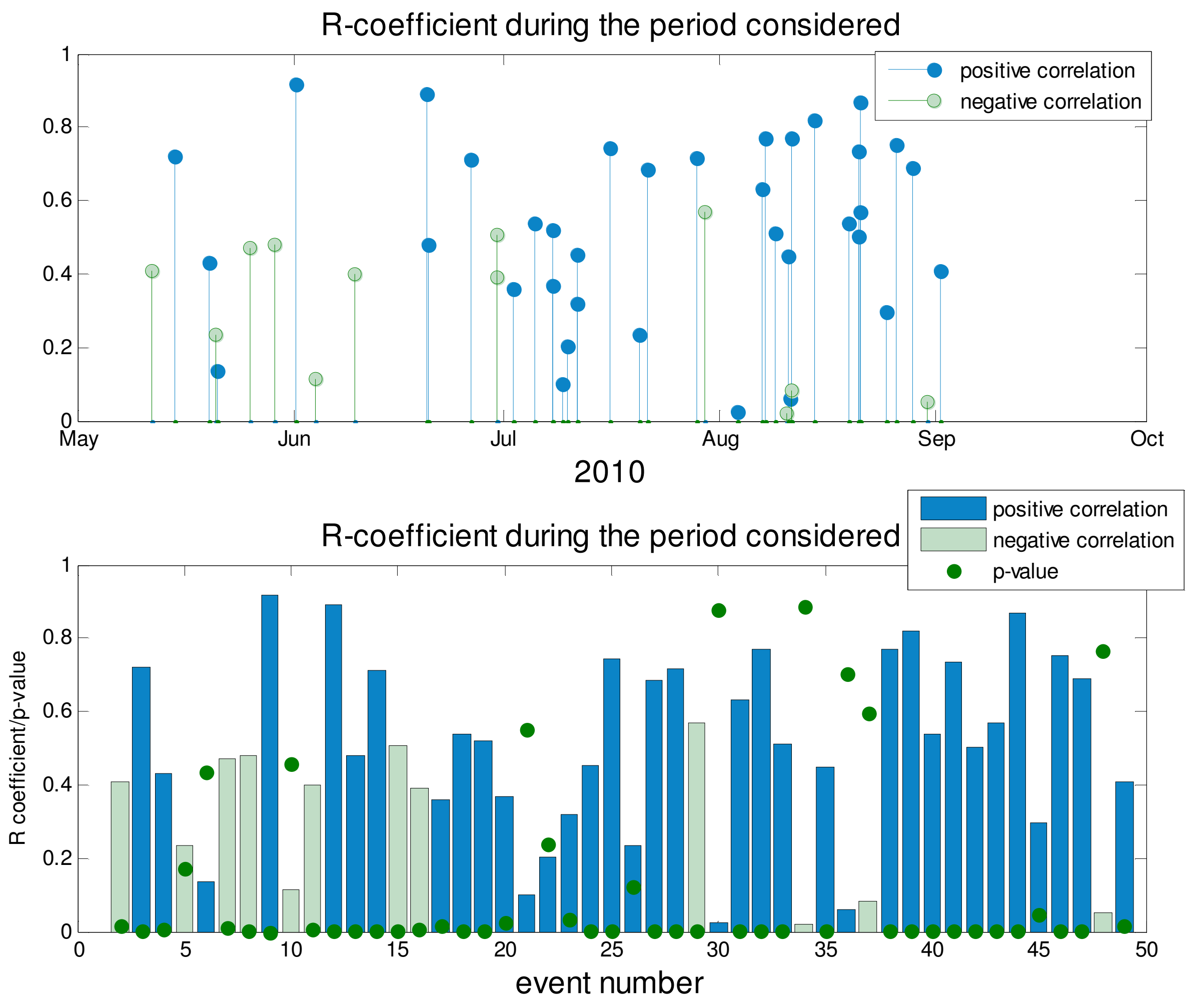

Figure 37- The correlation coefficient of the different comparisons as a function of the actual event (which was compared to the antecedent event)

Another variable, the number of dry days before an event, was investigated. No relation between the correlation of events and this variable could be detected. A graph illustrating this is added in the appendix. Even visually, no trend could be observed.

Comparison with multivariate analysis

The event 9 is sensitive to the latent heat flux. In the persistence analysis the magnitude of the correlation coefficient is also very high (R = 0.918). Both results confirm that this event is influenced by the precedent event. By contrast, event 8 is more influenced by the sensible heat flux and the correlation to the previous event is moderate and negative. The antecedent rainfall does not influence this event through induced evaporation fluxes (latent heat). In these two cases, the results are consistent for both analyses. The results of event 10 can not be compared, because the significance level in the persistence analysis is low.

The cluster group including events 4, 5, 6 and 7 do not have comparable results in the persistence analysis. The variable antecedent rain is not important for these events.

Considering the other cluster, the events 36 and 37 were not significative (high p-values) and for the other two (events 35 and 38) the correlation to the antecedent event is rather high.

II. II. Long-term persistence

The graph below shows the ten-days accumulation of rainfall as a function of the correlation coefficient. There is now apparent relationship between the two variables. Even in the case of intense rainfall over the last 10 days, the correlation coefficient is in certain cases relatively low.

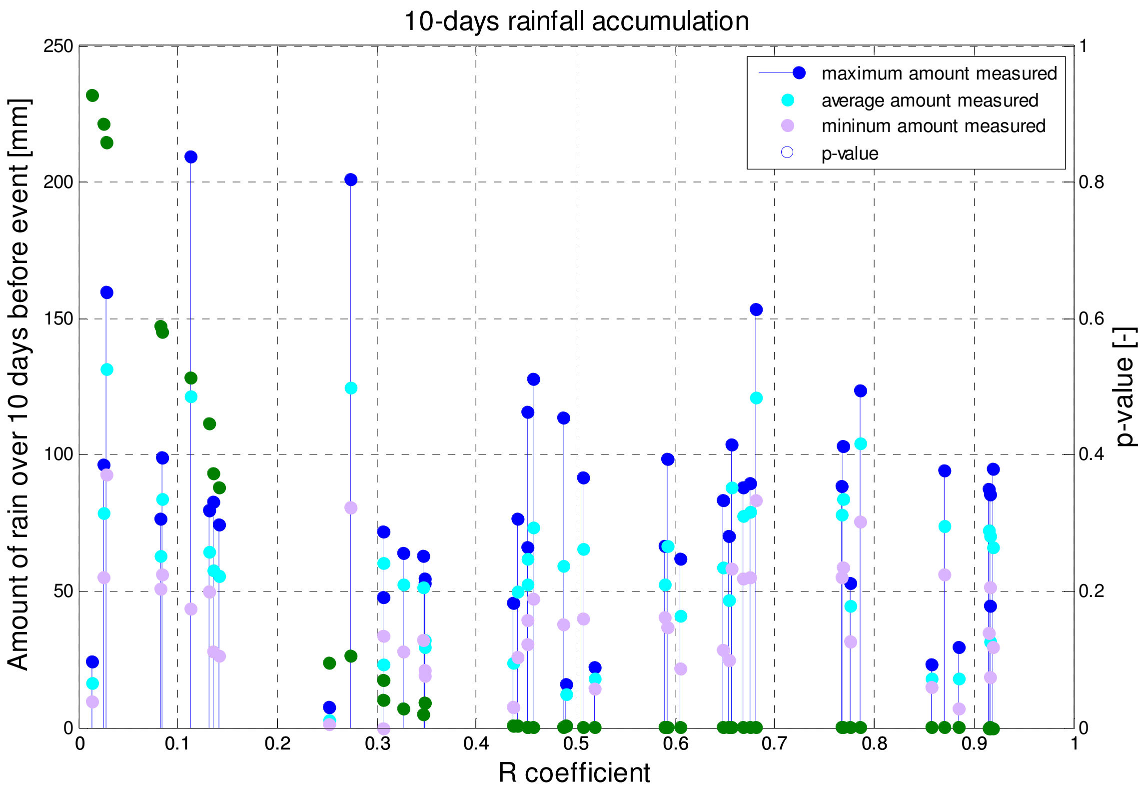

Figure 38- The influence of the 10-days accumulation of rainfall

The figure below shows the evolution of the correlation coefficient for the events considered. The graph is not similar to the one displaying the results for the short-lived persistence. The negative correlation observed here does not correspond to a negative correlation in the upper graph and vice versa. The opposite is rather a rule. This can be explained by the fact that some events are more influenced by bare soil evaporation (short-lived persistence) and others are more affected by the rainfall accumulated over a weeks in the soil (long-term persistence). Either one or the other effect is more pronounced. The contrast observed between the earlier months of the rainy season and the month of August does not appear on this graph anymore. Also, the events at which low significance is observed are not the same as above (events 7, 9, 18, 20, 23, 35, 39, 43).

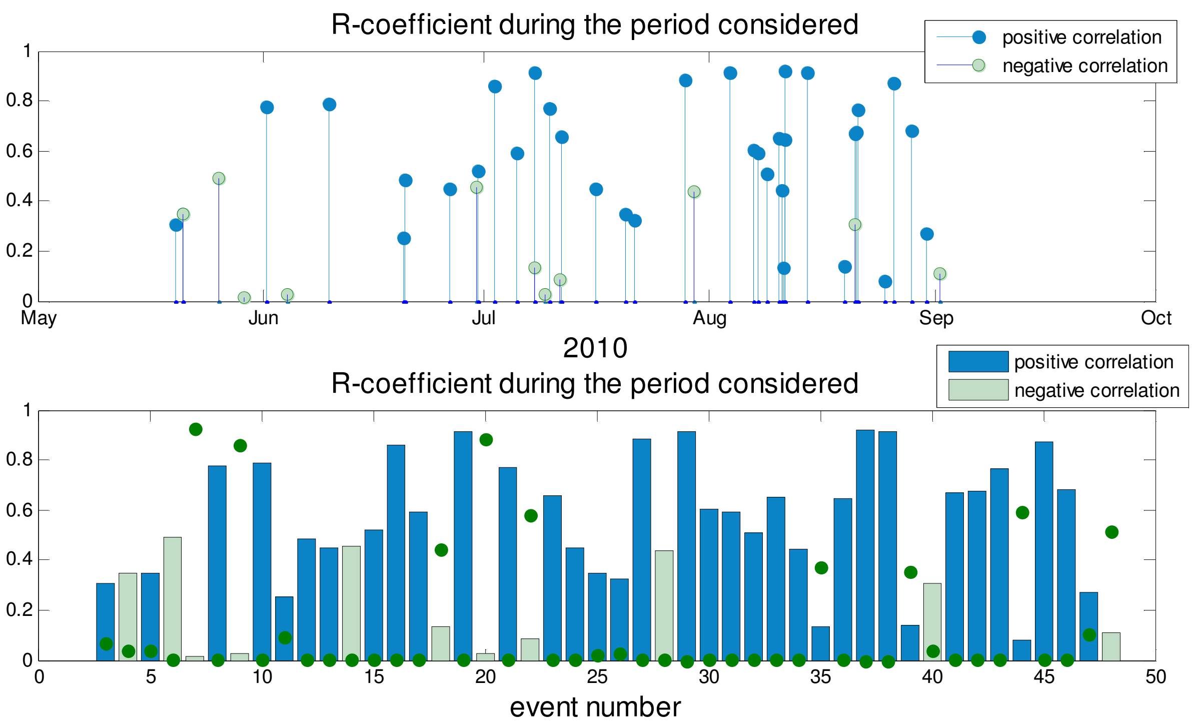

Figure 39- The correlation coefficient resulting from the comparisons as a function of the event considered (which was compared to the 10-days accumulation of rainfall differences)

b. Comparison hill-valley

I. Short-term persistence

The results are not similar to the results obtained in the first part of the analysis. In the figure below, there is no special distribution of the correlation coefficients in time. The magnitude of correlation is varying considerably. Considering exclusively the differences between the stations on the hill and the stations in the valley, the probability to obtain high correlation coefficients is high. Thus, the correlation coefficients are higher than in the first part. The differences between stations are more pronounced if comparing stations situated at a certain distance from each other and at a different height.

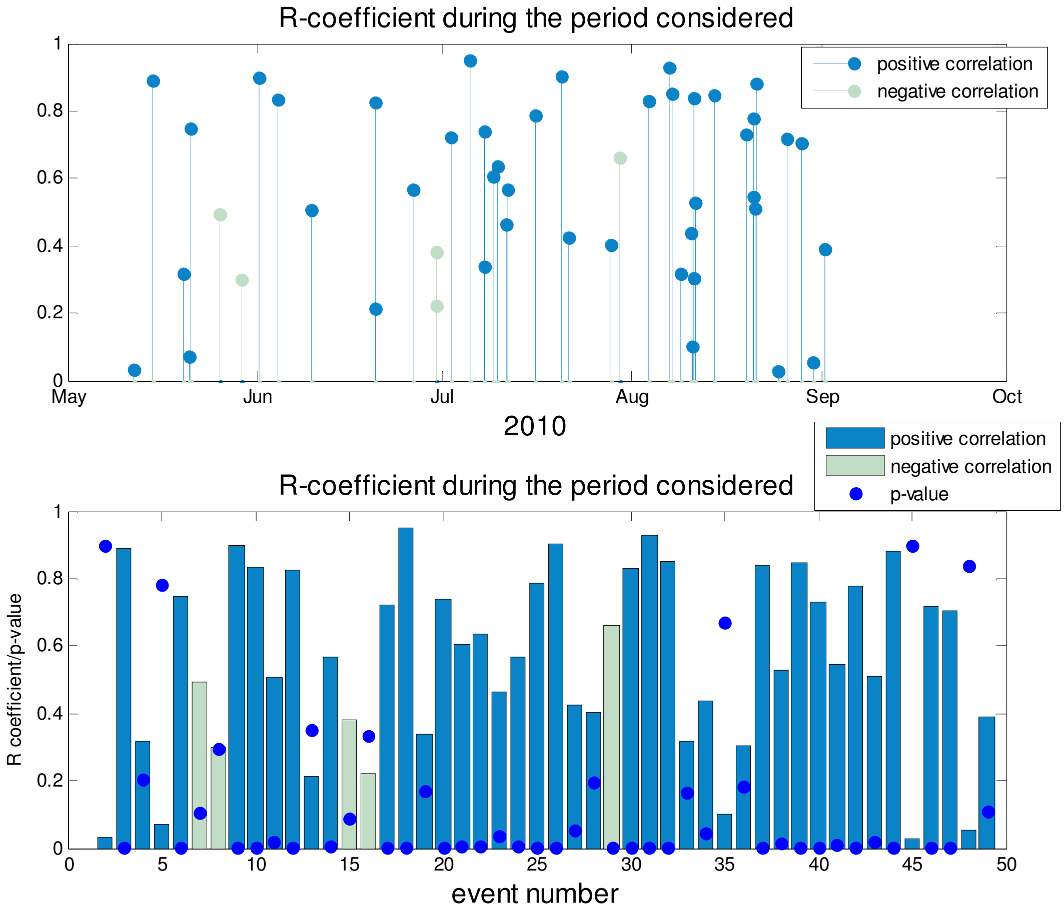

Figure 40- correlation coefficient for the short-lived persistence in the comparisons of differences between the stations situated on the hill with the stations in the valley.

The long term-persistence was not shown. There seems to be a risk of oversampling.

6.6 Conclusion

Taylor et al. (1997) showed in their study that Sahelian rainfall patterns exhibit persistence[27]. They concluded that intense storms, which pass over a land surface with pronounced gradients of soil moisture, the influence of the antecedent event is strong. The variable soil moisture can be due to another event only few days before. In the opposite case the spatial variability of the monthly rainfall can induce the storm. Therefore, both long-term and short-lived persistence was observed. In their analysis, they obtained always high coefficients of correlation.

In the persistence analysis, most often the correlation coefficients are high and the rainfall patterns of the events are positively correlated. However, as a contrast to the study of Taylor et al., also lower correlation coefficients which were not significative and negative correlations were obtained.

Generally, the fact that the rainfall patterns between the events are positively correlated indicates that certain persistence can be observed. This is true for short-lived persistence and even more pronounced for long-term persistence. It is not clear however, if other parameters also play an important role in the development of storms at the local scale. Also the observations are limited to an area which is smaller than the scale of a mesoscale convective system. It is possible that only a part of the resulting rainfall pattern is sampled. The local rather than the overal variability of the storm may be sampled, as the separation of the stations is of order of 100 meter. This leads to results which differ from the study of Taylor et al.

Another reason why the results are not the same as for Taylor et al. is the criteria defined which could not be applied to the data in the Singou river basin. These criteria ensure the success of the method. As all the criteria could no be applied, the risk of oversampling must be taken into account. Some characteristics of a mesoscale convective storm may be sampled several times, because the stations situated too close to each other. This problem is possibly more pronounced in the second part of the analysis in which the contrasts between the stations on the hill with the ones in the valley were analyzed.

[27] Taylor, Christopher M., et Thierry Lebel. « Observational Evidence of Persistent Convective-Scale Rainfall Patterns ». *Monthly Weather Review* 126, nº. 6 (juin 1998): 1597-1607.

Another problem constitutes the restricted time of observation. Therefore, the influence of the quantity of rain could not be described. However, as the project Info4dourou continues, new data will be available and the observations over several years allow statistical analysis.

One interesting result was obtained in the first analysis. The rainfall regime at the beginning of the rainy season has a different behavior as the one observed in August. In August, the events follow each other more closely and their influence on each other is growing. The intensity is not very high, but the events influence each other.

7 Infiltration experiments and time to ponding

The infiltration experiments in Tambarga allowed determining the hydraulic conductivity as well as the sorptivity of the soil at certain stations. These parameters are used together with the rain data to estimate the time to ponding. The time to ponding is a parameter of interest in the design of hydraulic structures in rivers. It corresponds to the time period between the moment when rain starts falling and the corresponding runoff is produced. The runoff data is used to verify if the estimation is correct.

7.1 Implications

The objective of the infiltration experiments was to determine the infiltration capacity. The infiltration capacity is the maximum rate at which soil of a certain type and under certain conditions can absorb water.[28] The Infiltration is a process of interest, because the part of the water infiltrated constitutes the major source of water for soil moisture and groundwater. A certain level of soil moisture must be sustained for vegetation growth and the groundwater is an important fresh water resource in the Sahel, where rain is absent over a longer period of the year. Mainly three factors are influencing the infiltration rate: the actual hydraulic properties of the soil profile, the rainfall intensity and the water content distribution.[29] Furthermore, the infiltration capacity is related to the generation of runoff. Runoff is observed when the rain rate is higher than the infiltration rate. It is expected that at the beginning of a rain event, no runoff is observed and only after a certain time the water starts ponding on the surface and flow occurs. A parameter of interest here is the time to ponding. This parameter is defined as the time period between the moment when the rain starts falling and the moment when runoff commences. Together with the quantity of runoff produced, this parameter is necessary for the design of hydraulic structures in the watershed (e.g. reservoirs) or irrigation systems.[30]

In the Sahel region, a phenomenon impacting the infiltration capacity is observed: the crust formation on the surface of soils induced by raindrop impact. However the rainfall is not solely responsible for this phenomenon. The extension of the cultivated surface and other farming activities (overgrazing, inappropriate farming techniques)[31] has some grave

28 Horton RE. 1933. The role of infiltration in the hydrologic cycle.Transactions of theAmerican Geophysical Union 14: 446–460.

29 Assouline, S., J. S. Selker, et J.-Y. Parlange. « A simple accurate method to predict time of ponding under variable intensity rainfall ». Water Resources Research 43 (mars 16, 2007): 10 PP.

30 Assouline, S., J. S. Selker, et J.-Y. Parlange. « A simple accurate method to predict time of ponding under variable intensity rainfall ». Water Resources Research 43 (mars 16, 2007): 10 PP.

31 « Importance of soil surface characteristics on water erosion in a small grazed Sahelian catchment - Karambiri - 2003 - Hydrological Processes - Wiley Online Library », s. d. http://onlinelibrary.wiley.com/doi/10.1002/hyp.1195/pdf.

consequences on the natural resources. To extend the surface used for agriculture, deforestation is necessary. Thus, grass, bushes and sometimes trees are burned and the protecting vegetation cover disappears. The surface becomes more sensitive to rainfall and erosion. On one hand erosion is favored and on the other hand a crust may form on the soil surface which does not allow water to penetrate the soil. Together with the dry conditions due to a decrease in the number of rainy days, desertification is favored. Even if the rainfall decreases, the risk of crust formation due to agricultural activities increases which translates in an intensification of runoff and diminishing of the water holding capacity. Thus the increasing agricultural activity is provoking an alteration of soil properties such as the infiltration capacity.

7.2 Questions

It is expected that the results of the measurements allow determining the time to ponding. Additionally, a model can be adjusted to the actual data of the time to ponding, since the times at which the rain and the runoff start is known.

7.3 Description of the practical part (Method)

The experiments were conducted in February 2012 during the dry season at 11 stations. Therefore, the soil was in a dry state at the moment the infiltration tests were carried out. Since the infiltration capacity depends also on the initial water content in the soil, the results would differ if the experiments were carried out another time of the year. The relationship between the initial water content and the infiltration capacity is not clear. Assouline et al. (2007) found that further research must be focused on the influence of antecedent soil moisture on the infiltration rate.

A minidisk infiltrometer manufactured by Decagon Devices, Inc. was employed. The infiltrometer is of cylindrical shape and consists of 2 chambers. The upper chamber is used to adjust the pressure head (bubble chamber). The lower chamber (reservoir) is graduated and the volume of water remaining can be read in milliliters. At the bottom of the cylinder is a disk, such that the water can only leave the bottom chamber, if there is contact with a solid surface.

At each station, three placements were selected for the experiment, so as to better assess the local variability of the observed parameter. Exactly at the same point the suction of 2 mbar and 4 mbar was subsequently applied in order to use the Gardner's equation presented further below. At the beginning the suction is adjusted and the infiltrometer is placed at the horizontal soil surface. At each time step, the remaining volume was noted.

7.4 Data treatment (Theory)

Then, the infiltration capacity is computed using Zhang's method. The cumulative infiltration, corresponding to the remaining volume at each time step, is expressed in terms of height [cm] and plotted against the square root of time with $t_o = 0$ s. To fit a second-order polynomial curve on this data, the following equation is used[32]:

$$I = C_1 t + C_2 \sqrt{t}$$

The hydraulic conductivity K is then calculated: $K = C_1 / A$

The constant A depends on the van Genuchten parameters n and α for a certain soil texture class.

$$\text{If } n \geq 1.9 \; A = \frac{11.65\,(n^{0.1}-1)e^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}}$$

$$\text{If } n < 1.9 \; A = \frac{11.65\,(n^{0.1}-1)e^{[7.5(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}}$$

where r_o is the radius of the disk and h_o the pressure head.

In the case of transient flow the following expressions were proposed for the two constants[33]:

$$C_1 = S_o$$

$$C_2 = K_n + 1/3\,(2-\beta)\,(K_o - K_n) + \frac{\gamma}{r_d(\theta_o-\theta_n)} {S_o}^2$$

The infiltration is thus modeled using three terms that describe different types of flow:

$$I(t) = So\,\sqrt{t} + \frac{7}{15} K_o t + \frac{0.75}{r_d(\theta_o-\theta_n)} {S_o}^2 t$$

[32] Zhang, Renduo. « Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer ». *Soil Science Society of America Journal* 61, n°. 4 (8/01 1997): 1024-1030.

[33] Angulo-Jaramillo, F., J.P. Vandervaere, S. Roulier, J.L. Thony, J.P. Gaudet, and M. Vauclin. 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments. Soil Till. Res. 55:1-29. Schwartz, R.C. 2001. Influence of soil layering on infiltration

From left to right on the right side of the equal sign, the terms correspond to the vertical capillary flow, the gravity-driven vertical flow and the lateral capillary flow. It is assumed that the gravity and lateral capillarity term can be neglected and the sorptivity S_o is estimated as follows: $I(t) = S_o t^{1/2}$

Consequently, the sorptivity is deduced from the slope of the linear curve by fitted on the graph showing S_o as a function of the square root of time. This formula is a simplification and the estimation of sorptivity has certain limitations. For instance, for sandy soil the gravity term can become important. On the other hand, in the case of clayey soil the lateral capillary flow may not be neglectable. Moreover, the time step also affects the value of S_o obtained.

The method used here is the multiple head approach. As two suction rates were subsequently applied at the same location, Gardner's equation can be used which describes the relationship between the hydraulic conductivity K and the pressure head h[34]:

$$K(h) = K_{fs} e^{\gamma h}$$

The unknowns are the apparent field-saturated hydraulic conductivity K_{fs} and the constant γ. The γ constant is a measure of capillary forces. Knowing the hydraulic conductivity at two different pressure heads (2 cm and 4 cm), the equation can be solved for the two unknowns.

[34] Angulo-Jaramillo, F., J.P. Vandervaere, S. Roulier, J.L. Thony, J.P. Gaudet, and M. Vauclin. 2000. Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments. Soil Till. Res. 55:1-29. Schwartz, R.C. 2001. Influence of soil layering on infiltration

7.5 Results of the practical part

The values of sorptivity [cm/s$^{1/2}$] obtained for the three placements at each station are the following:

Table 20-The sorptivity values for all the stations

station	points	S [cm/s$^{1/2}$]	station	points	S [cm/s$^{1/2}$]
station 1010	1	0.30	station 1264	1	0.20
	2	0.20		2	0.20
	3	0.15		3	0.18
station 1008	1	0.23	station 1006	1	0.13
	2	0.11		2	0.12
	3	0.25		3	0.13
station 1160	1	0.30	station 1263	1	0.30
	2	0.33		2	0.15
	3	0.36		3	0.17
station 1009	1	0.16	station 1007	1	0.28
	2	0.11		2	0.15
	3	0.15		3	0.20
station 1005	1	0.19	station 1001	1	0.34
	2	0.21		2	0.11
	3	0.25		3	0.21
met2 & précis	1	0.13	station 1262	1	0.09
	2	0.14		2	0.19
	3	0.17		3	0.24

The values of k_s [mm/h] depend on the soil texture of the soil considered. In the following table the values obtained for three soil texture classes are shown:

Table 21-the hydraulic conductivity values at the stations

station	points	loamy sand	silt loam	silty clay loam	station	points	loamy sand	silt loam	silty clay loam
station 1010	1	179.19	83.70	111.21	station 1264	1	119.13	55.65	154.26
	2	152.94	71.44	167.79		2	155.40	72.59	134.70
	3	119.13	55.65	154.26		3	141.00	65.87	173.89
station 1008	1	108.15	50.52	167.79	station 1006	1	47.81	22.33	281.29
	2	24.82	11.60	478.19		2	55.69	26.02	562.58
	3	141.84	66.26	170.78		3	84.56	39.50	265.66
station 1160	1	242.16	113.12	66.42	station 1263	1	358.55	167.49	91.96
	2	390.51	182.42	69.81		2	46.50	21.72	140.64
	3	604.74	282.49	59.04		3	197.02	92.04	170.78
station 1009	1	82.27	38.43	258.48	station 1007	1	255.22	119.22	113.86
	2	36.02	16.83	531.32		2	88.72	41.44	258.48
	3	48.68	22.74	258.48		3	235.59	110.05	116.63
station 1005	1	83.11	38.83	162.10	station 1001	1	575.51	268.84	239.10
	2	129.82	60.64	127.52		2	34.13	15.94	503.36
	3	140.20	65.49	129.24		3	146.18	68.29	156.78
met2 & précis	1	58.06	27.12	341.57	station 1262	1	31.56	14.74	318.79
	2	68.11	31.82	191.28		2	309.35	144.51	103.95
	3	85.06	39.73	222.41		3	220.39	102.95	112.52

The values of conductivity are highly variable throughout the watershed. Consequently, additional to the rainfall variability, the heterogeneity of the land surface and the topography also influences the final distribution of the water. In particular, spatial variability of conductivity is also observed at a local scale. At each station three observations were made from points separated by only a few meters. The three values differ considerably for most of the stations. These variabilities occurring at different spatial scales reveal the complexity of the phenomena studied.

The three soil texture classes shown in the table are considered having the same properties as the soil in the watershed. In the determination of the time to ponding, the average value of the three conductivity values obtained for these classes is considered. Only the data of the stations is used which were considered being reliable in the analysis of rainfall, because the rainfall data is necessary to determine the time to ponding. The conductivity data used in the calculation is colored in purple in the above table. The following map shows the positions of the stations eventually selected in the analysis and the corresponding points at which the experiments were conducted

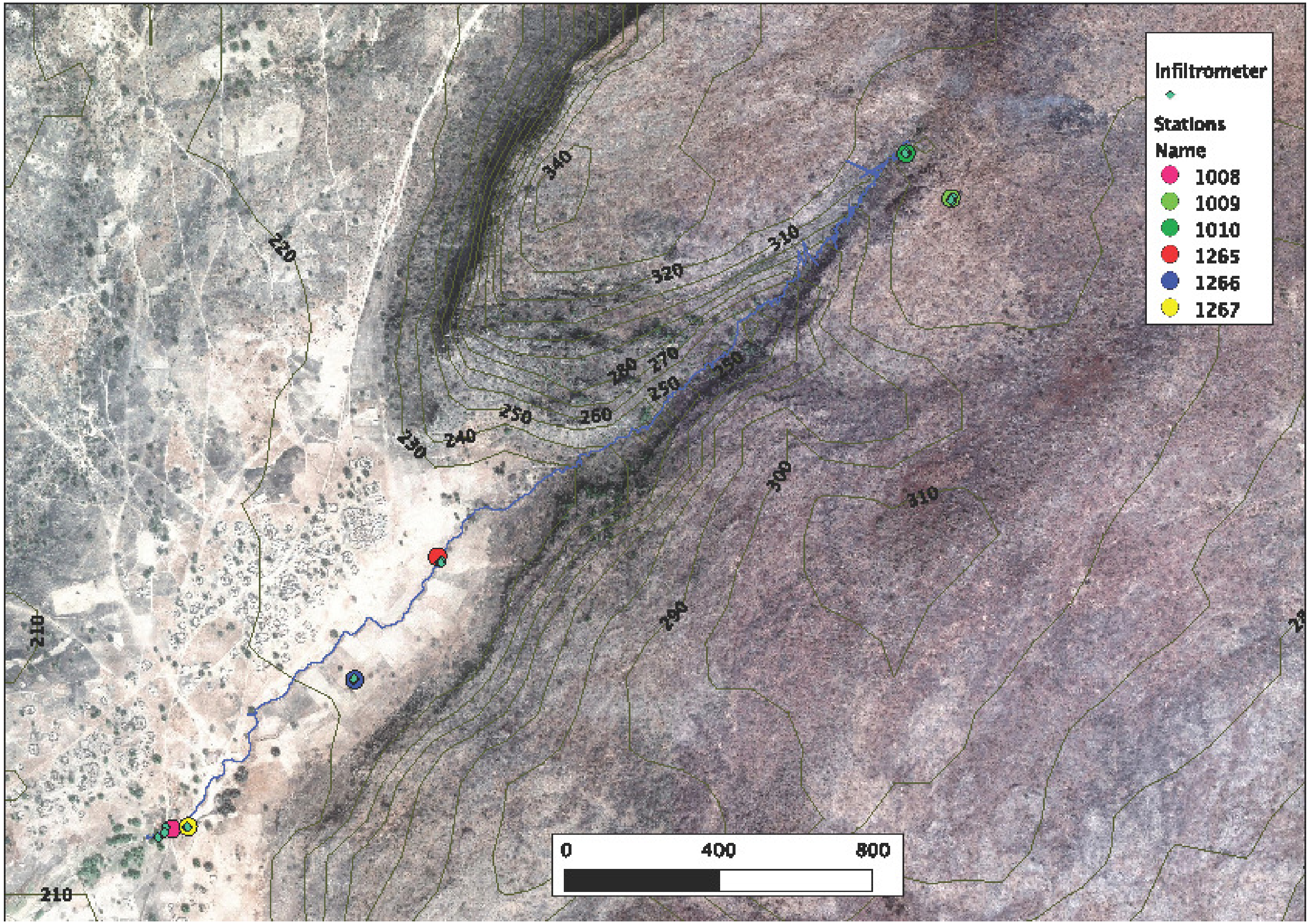

Figure 41 Map showing the locations of the infiltration experiments

Determination of the time to ponding[35]

The time to ponding is the time period between the beginning of rainfall and the runoff. Figure 29 illustrates this. The black curve represents the rain and the blue curve the discharge response.

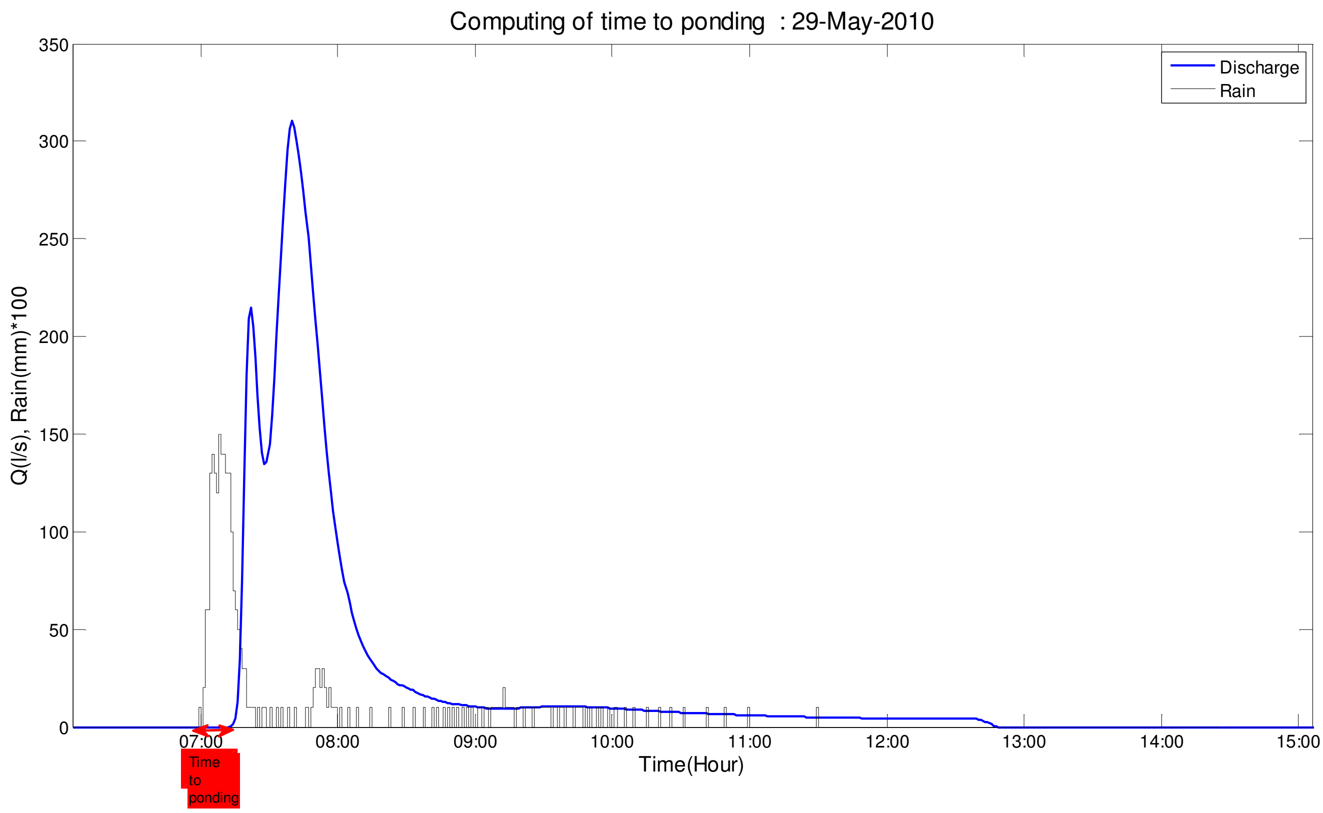

Figure 42- Definition of the time to ponding-the difference between the start times of runoff and rain

The time to ponding is derived from Richards's equation for vertical migration of water in soil:

$$\frac{d\theta}{dt} = -\frac{d}{dz}\left(k\frac{dH}{dz}\right) - \frac{dk}{dz} = \frac{d}{dz}\left(D_w\frac{d\theta}{dz}\right) - \frac{dk}{dz}$$

where:

-H: water suction [L]

[35] Brutsaert, W. (2005). Hydrology: An introduction. Cambridge: Cambridge University Press.

-z: the vertical axis with positive values in the downward direction

-θ: water content [-]

-k: hydraulic conductivity [L/T]

The second equation is the diffusion formulation of vertical infiltration of water ponding on the soil surface. The equation of the time to ponding is derived using the sharp front approach. The assumption is made that there is a sharp wetting front, such that the area passed by the front is practically fully saturated. The water content doesn't vary significantly after the passage of the wetting front and the term on the left hand side of Richards's equation can therefore be neglected. The infiltrated volume corresponds to the integration of the water content over the depth or to the integration of the precipitation rate over time. Hence they are equal and the following relationship applies:

$$\int_0^{tp} P\,dt = -\int_{\theta i}^{\theta o} \frac{(\theta - \theta i)D_w}{(P - k)} d\theta$$

Where:

P: the rain rate [L/T]

D_w: soil water diffusivity [L^2/T]

Θ_o : water content at satiation and at z = 0 (surface) [-]

Θ_o : water content at z = z_f (position of the wetting front) [-]

t_p: time to ponding [T]

The time to ponding is considered being the time required of the soil surface water content to reach saturation. Thus, the hydraulic conductivity can be replaced by $k = k_o S_e^n$ and the diffusivity by $D_w = k_o\, \alpha\, S_e^{\beta}$.

Solving for t_p gives:

$$t_p = \frac{H_b(\theta_o - \theta_i)k_0}{\langle P\rangle b} \int_0^1 \frac{{S_n}^{n-1/b} dS_n}{(P - k_o {S_n}^n)}$$

P: average precipitation rate during the event until the onset of ponding [L/T]

Substituting the sorptivity $A_o = 2(\theta_o - \theta_i)[D_o/\pi]$ into the equation and after integration gives: $t_p = \frac{{A_o}^2}{2Pk_o} \ln\left(\frac{P}{P-k_o}\right)$.

Additionally, the assumption is made that the rainfall rate is constant during the storm. The above equation can be expressed with dimensionless variables. The time to ponding and the precipitation rate are scaled: $t_{p+} = \frac{{k_o}^2 t_p}{{A_o}^2}$ and $P_+ = P/k_o$

Thus the following formula is obtained: $t_{p+} = \frac{\alpha_p}{P_+} \ln\left(\frac{P_+}{P_+ - 1}\right)$

where $\alpha_p = 0.55$ is a constant used if the properties of the soil are not known.

7.6 Criteria

There are certain requirements concerning the data which is used to compute the time to ponding. First of all, the rain should not have a dispersed pattern such that the beginning of an event can be easily identified. This criterion is fulfilled if the same criteria are applied as used to identify the different events. Therefore, the data concerning the different rain events was directly considered in this analysis. The second criterion concerns the runoff. Likewise, the start of runoff must be clearly identifiable. If the diurnal fluctuations of water flow in the river cannot be distinguished from the changes induced by the rain, the event in question was not considered in this analysis. The third criterion is imposed by the formula of time to ponding used. In the formula in which the dimensionless variables are employed, the tp_+ only gives a realistic estimate, if the precipitation rate P is greater than the value of k_o. In the opposite case, the scaled value of P will become smaller than one and the whole term in the natural logarithm is negative.

7.7 Results

The graph below shows the ponding time as a function of rain intensity for the six stations considered. The blue scatters are the values obtained with the equation using the data from the infiltration experiments as an input. The other scatters are obtained directly calculating the time to ponding considering the dates of the beginning of the rain event and the runoff, and subsequently plotting it against the rain intensity of the event. The Singou River is ephemeral. In 2010, runoff was only observed on the 7th of July at the basin outlet. Before, the riverbed was empty. At this time, the runoff was only observed in the lower part of the catchment. The continuous flow established ending August and the sources situated in the upper part also contributed to the runoff. The green points correspond to the conditions of continuous flow (AF = after establishment of continuous flow conditions). The red series correspond to the events before (BF) the continuous flow was observed (between the 7th July and ending August).

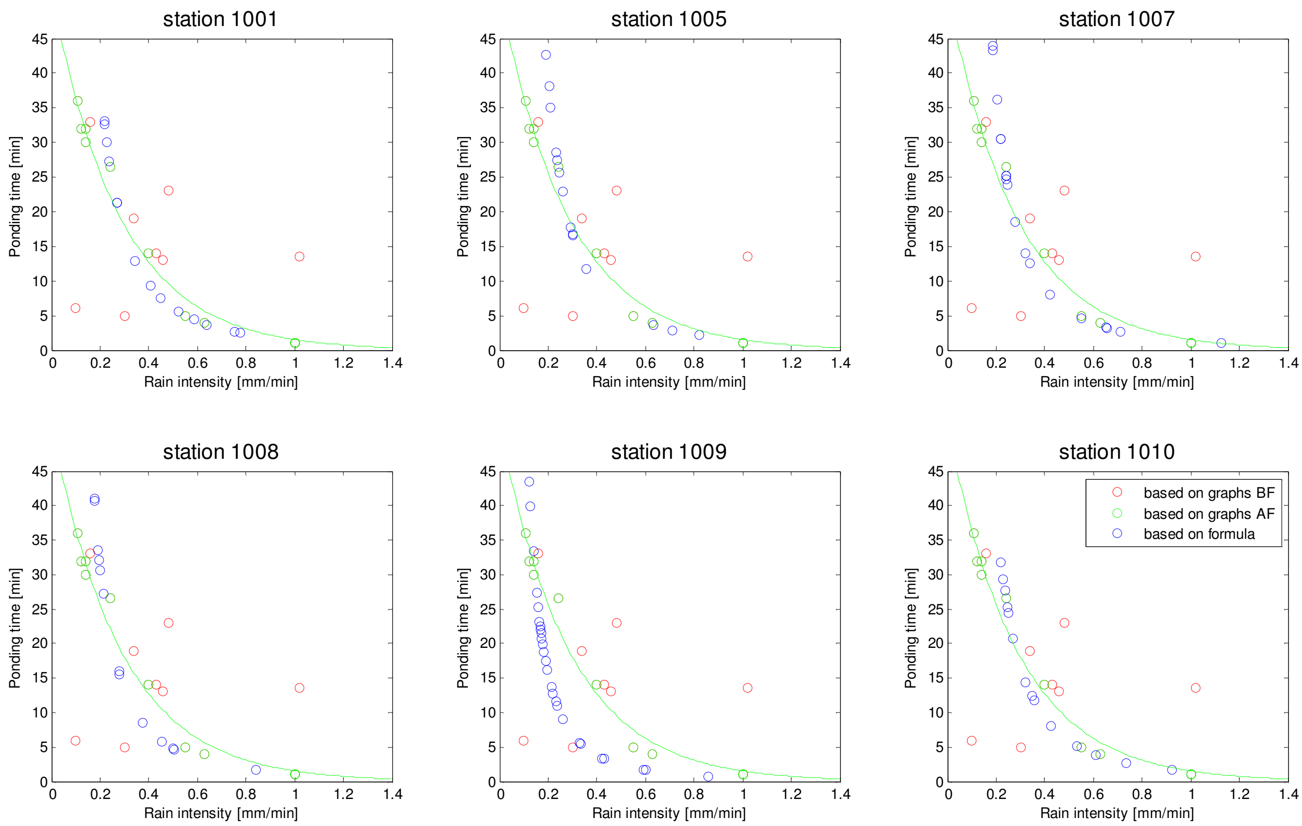

Figure 43- The ponding time as a function of average rain intensity of an event

7.8 Discussion

Regarding the blue points, the time to ponding is decreasing with increasing rain intensity, as it follows the law from the formula used. The same relation can be found for the green data points, at which a model was fitted. However, it was not possible to fit a model to the data series representing events before a continuous river regime is established (red scatter). An explanation for this is that the factors influencing the time of ponding (e.g. soil moisture or water holding capacity) vary considerably before continuous flow is observed. During this period, these factors have a larger influence than the rainfall only, which is also less regular.

7.9 Conclusion

For the ephermal and temporal river the time to ponding base on Richard's formula is only valid for the period when the flow in the river is continuous over its whole length and without any contribution of rain. The ponding time for the drier river cannot be approximated with the formula.This can be explained by other factors which have a greate influence if the flow is not continuous. The role of parameters such as antecedent soil moisture as well as other soil properties needs to be examined in more detail.

The estimation of the time to ponding can be improved, if the values of conductivity are computed for different soil moisture states. Moreover, this information could then also be integrated in the estimation of the sorptivity and the hydraulic conductivity.

8 Conclusion

The Sahel is a semi-arid region which is characterized by a high spatio-temporal variability of rainfall. For rural communities rain is an important factor, since their livelihood mainly depends on the agriculture. Generally speaking, the agriculture in West Africa is essentially rainfed.

A network of 13 sensorscope stations is installed in the catchment of the Singou River. They measure meteorological parameters continuously (at a 5 minutes time step). Thus, a part of the spatio-temporal variability of rainfall in the catchment is recorded. As pointed out in the introduction to the thesis, information on rainfall is crucial for famers and helps them in their decisions and farming strategies.

The sensorscope stations are equipped with Davis rain gauges. In section 2 of this thesis the accuracy of the rain gauges was evaluated, which gave the following results. An error range of +-15% was found for the data from the Davis rain gauges in the case of low intensities. At higher intensities the mechanical parts may not function well and underestimation of the actual rain amount is possible. As for the précis rain gauge a constant underestimation of 50% was obtained. A correction factor of *2 can be applied to the data from the précis rain gauge. For the stations in Tambarga, it must be taken into account that additional external factors such as wind, can falsify the measurements as well.

In section 3, the data of the stations in Tambarga was evaluated and ten stations were considered reliable. The data from these stations was subsequently used in the analyses presented here. The period of study was defined as well (May to August 2010). As the dataset was chosen, the events for this period were identified following certain criteria. In June some heavy rainfall events were detected. The frequency of events was rather low. By contrast, in August the intensity of rain was generally lower, but the frequency of the events was considerable.

The researcher can evaluate the rain events only in a restricted way, in terms of quantity and intensity. Therefore indigenous knowledge on rainfall is important. The farmers have another way of thinking and describe rain as different rain types. The quantity is not the solely important factor. In the survey, different rain types were assessed and the criteria of rain which were important to the villagers were identified. The quantity, the regularity of the rain and the wind were the most cited characteristics of a rain event. Another survey can be designed on the basis of this survey and including questions about rain forecast as well.

The conditions which trigger a rain event were considered in section 5. The influence of the soil moisture, the antededent rain, the latent heat flux, the sensible heat flux and the rain height were considered using PCA. The PCA was carried out for 4 selected stations. The distribution of the events showed a similar pattern for all the stations. It was found that if the value for variable sensible heat is large, an event of the same type as event 8 is probable to be observed. Likewise, the event 9 is influenced by latent heat fluxes. A cluster of events was identified (events 4,5,6,7) . These events are probable if the value for soil moisture is low. Moreover, these rain events occur at the beginning of the rainy season when the soil is still dry.

The persistence of rainfall patterns in the Singou river basin was analyzed in section 6. The persistence is observed in the case when all the reliable stations are included. The correlation coefficients at the beginning of the rainy season are variable and relatively low. In August the correlation coefficients are high and the correlation between the rainfall pattern of the actual event to the antecedent event is always positive. This is an interesting result. The behavior of the rain events in August is different as that of the events observed earlier in the rainy season. In August, the dry period between two events is comparatively low and sometimes 2 or 3 events are identified for one day. The intensity is not considerably high, but they are influencing each other.
The question arises, if the beginning of the rainy season allows predicting the rainfall pattern observed in August. It is difficult to establish a link over a longer period as single events were considered here. Also for the months of July and August, the long-term persistence part showed that the values of positive correlation are rather high, hence, a certain influence is possible. The comparison considering only the difference between stations on the hill with the one in the valley, give even better correlation coefficients. The differences between those stations are probably more marked as the distance and the denivellation is larger.

In the last section the validity of the of the time of ponding derived from Richard's formula for the Singou River catchment was evaluated. The Singou River is an ephermal river with different regimes. It is distinguished between the period during which only the lower part of the basin contributes to runoff and the period during which continuous flow along the whole river is observed. The validity of Richard's formula could only be proven in the case of continuous flow. During the other period other parameters related with the soil may have a larger influence. The formula does not take into account these factors.

In the future, as the project in Tambarga continues, future research concerning the rain data can be continued in several ways. The multivariate analysis could be carried out with a larger set of data. Also the evaluation of the accuracy of the rain gauges can be improved by the estimation of the error as a function of the rainrate. As for infiltration, it is known that the infiltration rate depends on the initial water content. The infiltration experiments presented in this thesis were carried out during the dry season and the initial soil moisture at the surface was very low. It would be interesting to see how the results change if the same experiment was carried out in more humid conditions. At lower rain rates, the Davis rain gauges can present very accurate results. As the intensities measured in Tambarga are rather low, the data may be used for further analysis.

The variability of rainfall was considered in this thesis from different angles. The multivariate analyisis and the persistence analysis yielded some consistent results. On the other hand each the analysis has its own limitations and a part of the results could not be compared, because they were not significant. Another difficulty lies in the fact that the factors involved in the development of storms are various and the processes complex, so that no simple linear relationships can be detected. In general it was shown that different types of events exist and that sometimes a variable has more influence in the triggering of a storm than others.

Additionaly to the variability of rainfall, the final distribution of water in the watershed, in the form of soil moisture groundwater or runoff, is determined by the land surface. The heterogeneities of the soil surface result also in different infiltration capacities and the final amount of water available for the plants as soil moisture depends on both, infiltration capacity and rain.

9 Bibliography

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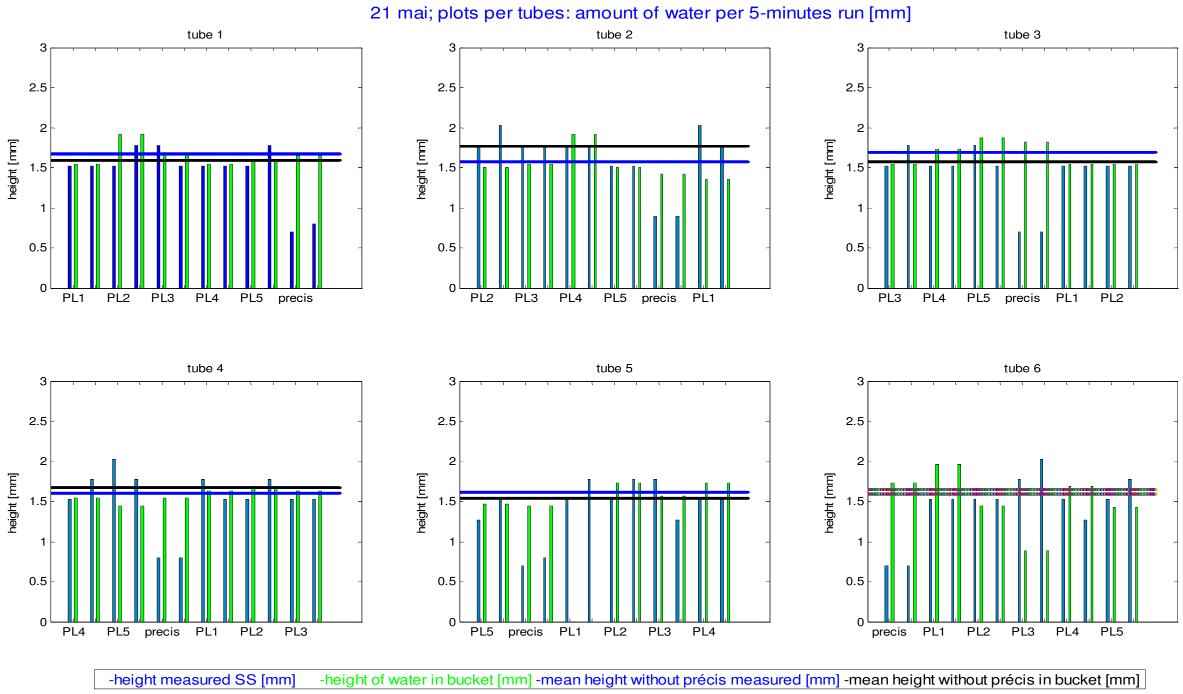
10 Appendix

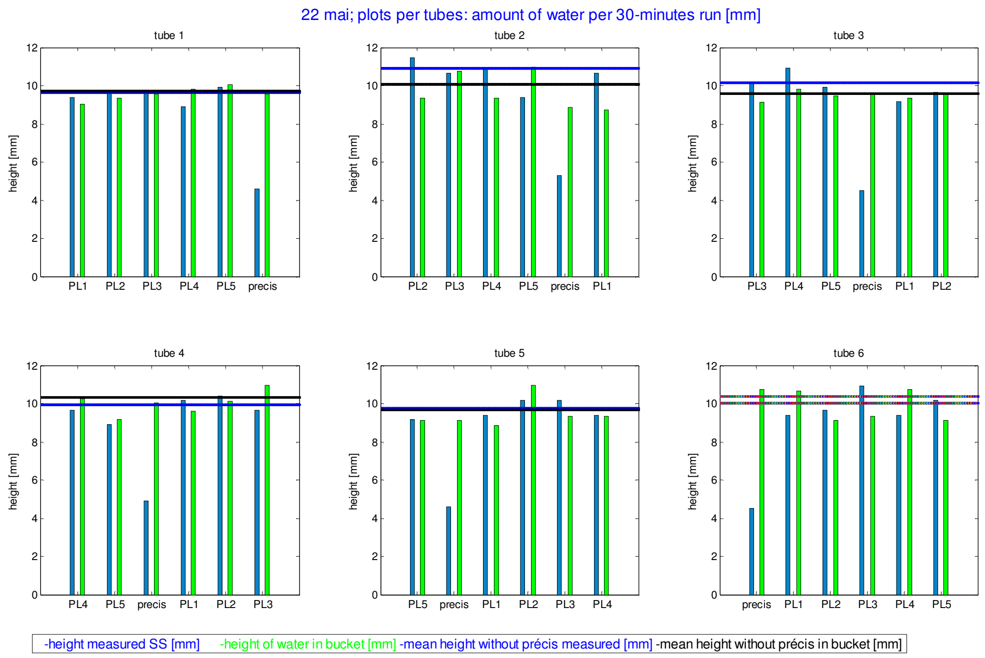
10.1 Events

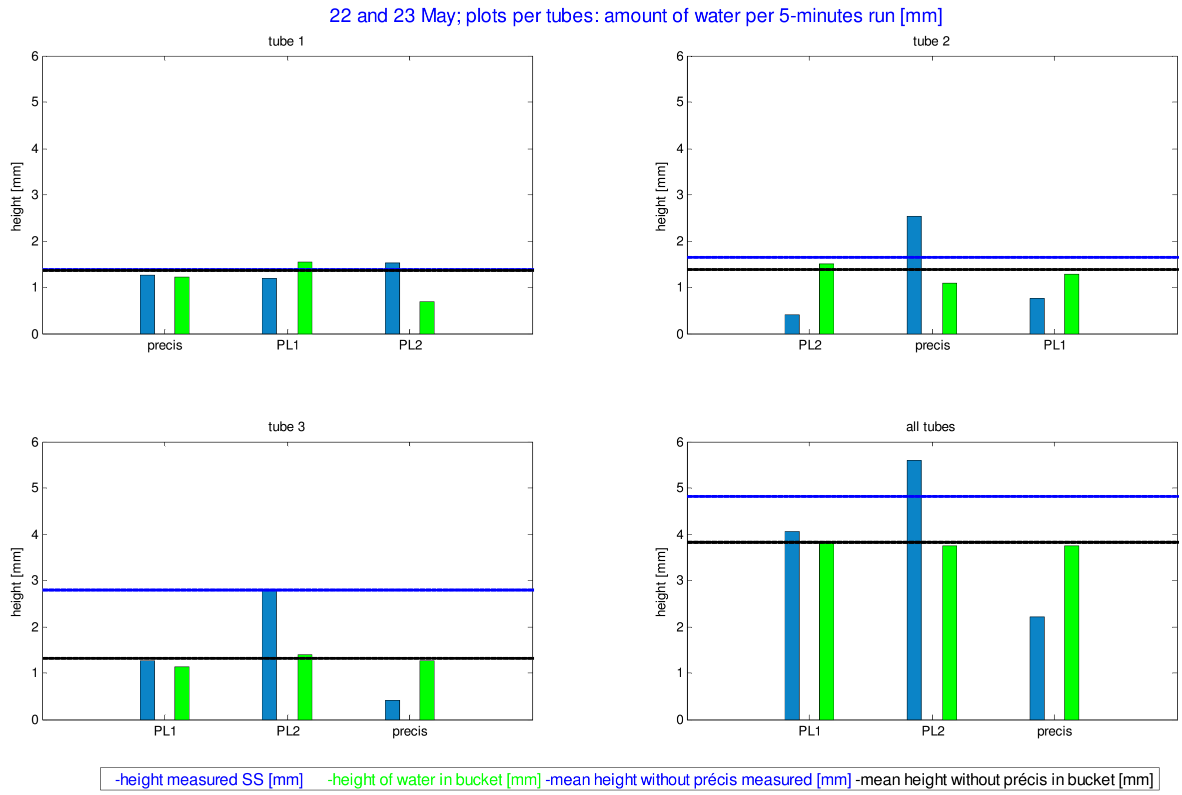
Data of station 1001

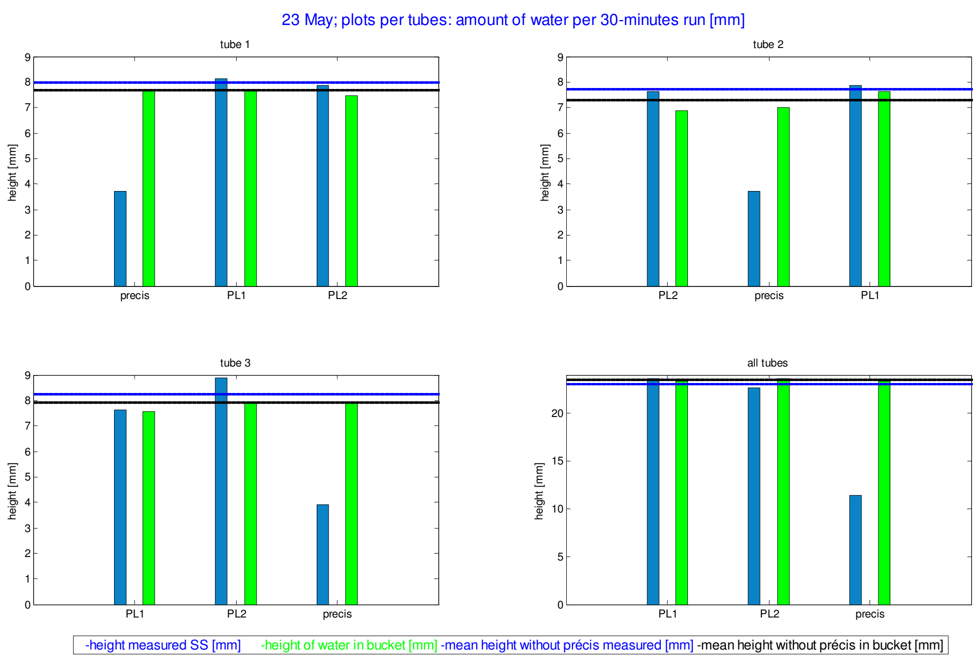
event nr.	Start date	event nr.	Start date
1	5/7/2010 6:20	26	7/20/2010 12:55
2	5/11/2010 18:25	27	7/21/2010 16:00
3	5/14/2010 20:00	28	7/28/2010 16:45
4	5/19/2010 20:05	29	7/29/2010 22:50
5	5/20/2010 20:05	30	8/3/2010 15:45
6	5/20/2010 23:05	31	8/7/2010 2:10
7	5/25/2010 18:35	32	8/7/2010 13:25
8	5/29/2010 7:05	33	8/8/2010 21:10
9	6/1/2010 5:55	34	8/10/2010 14:10
10	6/4/2010 4:45	35	8/10/2010 19:55
11	6/9/2010 19:25	36	8/11/2010 3:30
12	6/20/2010 3:20	37	8/11/2010 5:20
13	6/20/2010 5:35	38	8/11/2010 8:30
14	6/26/2010 7:30	39	8/14/2010 11:10
15	6/30/2010 2:55	40	8/19/2010 13:30
16	6/30/2010 4:20	41	8/20/2010 21:40
17	7/2/2010 11:45	42	8/20/2010 22:50
18	7/5/2010 11:45	43	8/21/2010 0:00
19	7/7/2010 23:55	44	8/21/2010 5:30
20	7/8/2010 1:20	45	8/24/2010 22:20
21	7/9/2010 9:45	46	8/26/2010 4:40
22	7/10/2010 1:50	47	8/28/2010 14:50
23	7/11/2010 12:05	48	8/30/2010 15:30
24	7/11/2010 15:25	49	9/1/2010 12:05
25	7/16/2010 8:45		

10.2 Experiments



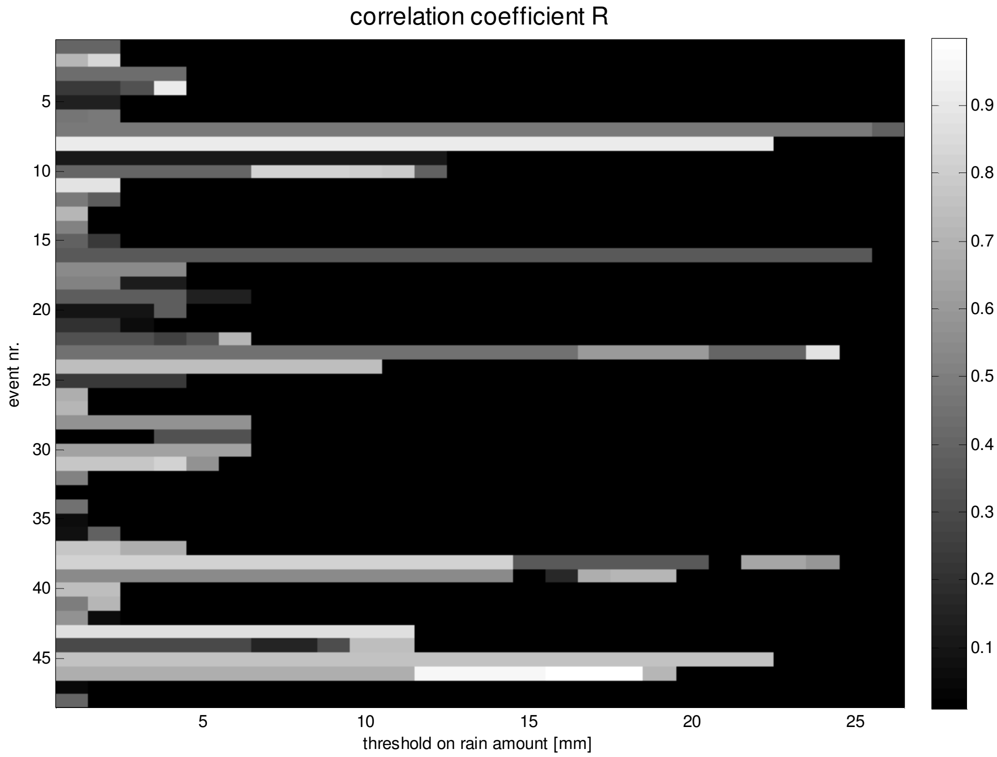



22 and 23 May; plots per tubes: amount of water per 5-minutes run [mm]
tube 1
tube 2
tube 3
all tubes
height [mm]
precis
PL1
PL2
-height measured SS [mm]
-height of water in bucket [mm]
-mean height without précis measured [mm]
-mean height without précis in bucket [mm]

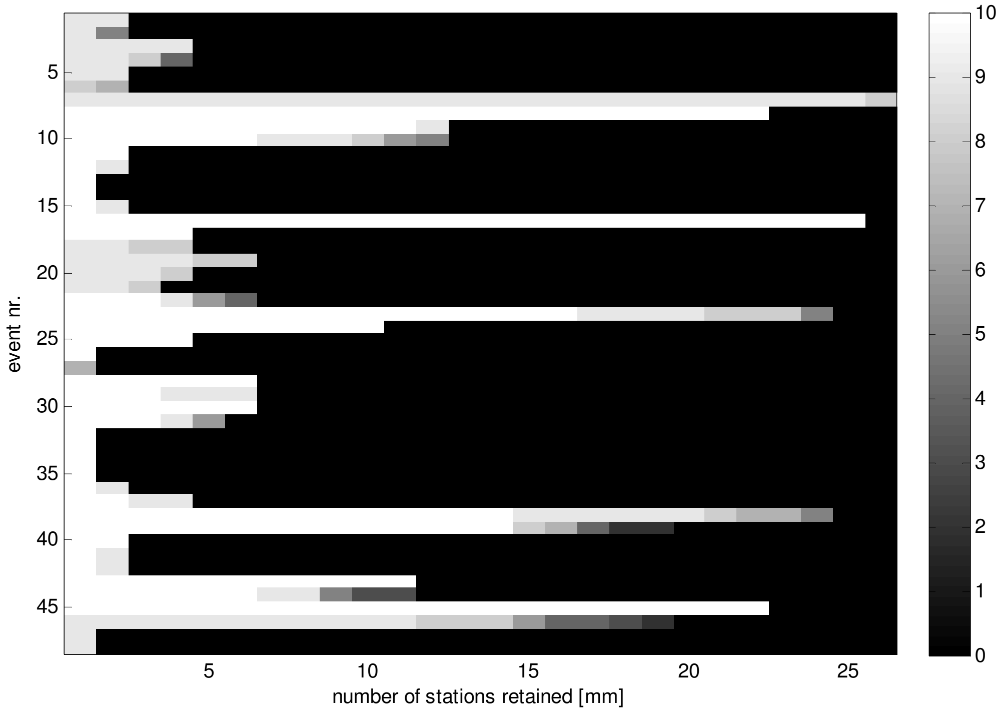

23 May; plots per tubes: amount of water per 30-minutes run [mm]
tube 1
tube 2
tube 3
all tubes
height [mm]
precis
PL1
PL2
-height measured SS [mm]
-height of water in bucket [mm]
-mean height without précis measured [mm]
-mean height without précis in bucket [mm]

10.3 Persistence Analysis

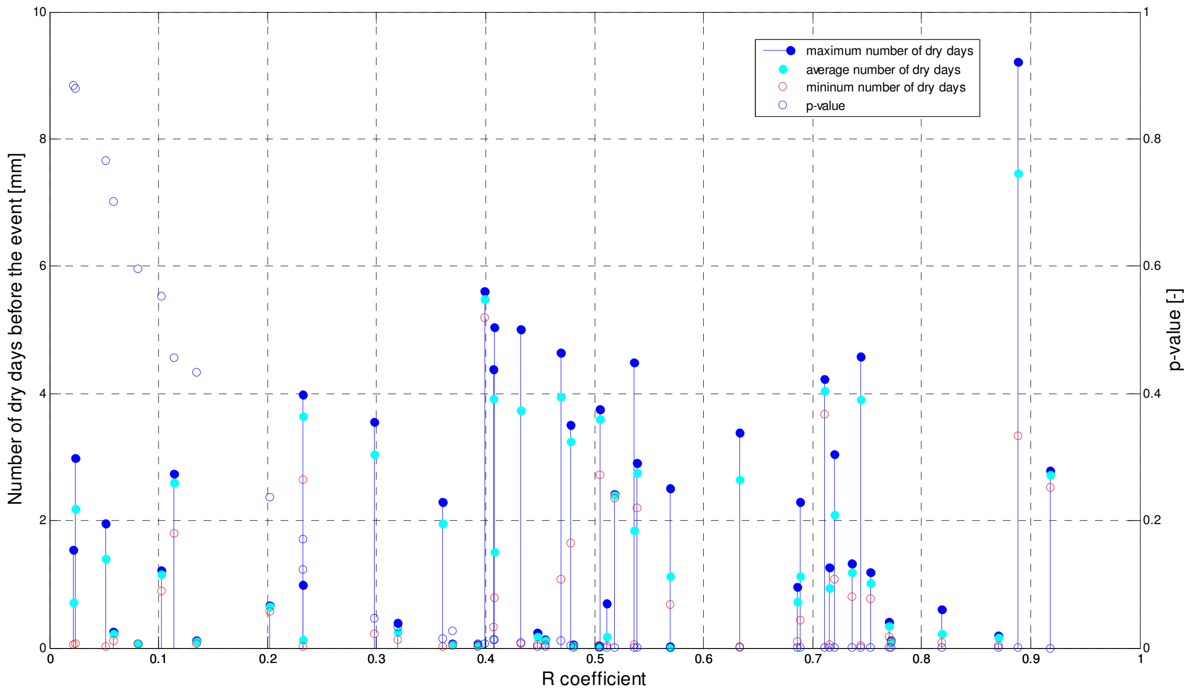
The correlation coefficient is shown as a function the event and the threshold on the rain amount. As the threshold increases, stations which measure less than others are excluded from the comparison. Sometimes this leads to a larger R coefficient and sometimes the coefficient is smaller. It depends on the data of the station excluded. If the station did measure at one of the two events remarkably different compared to the other stations, the values of the differences also become extreme and the correlation coefficient becomes small. If such a station is excluded, the result is an increase in the correlation. To see how the correlation coefficient evolves, each comparison separatedly has to be considered in more detail.



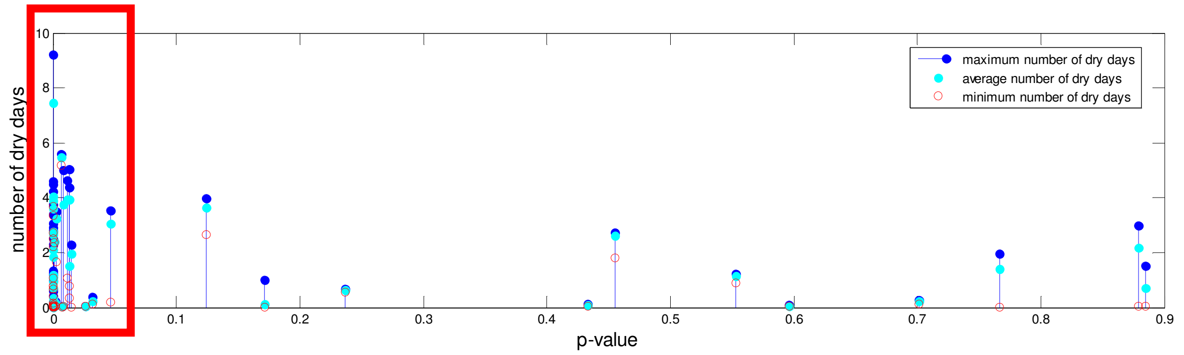
The figure below shows the number of stations retained for a certain comparison. As its value changes, also the correlation coefficient changes.

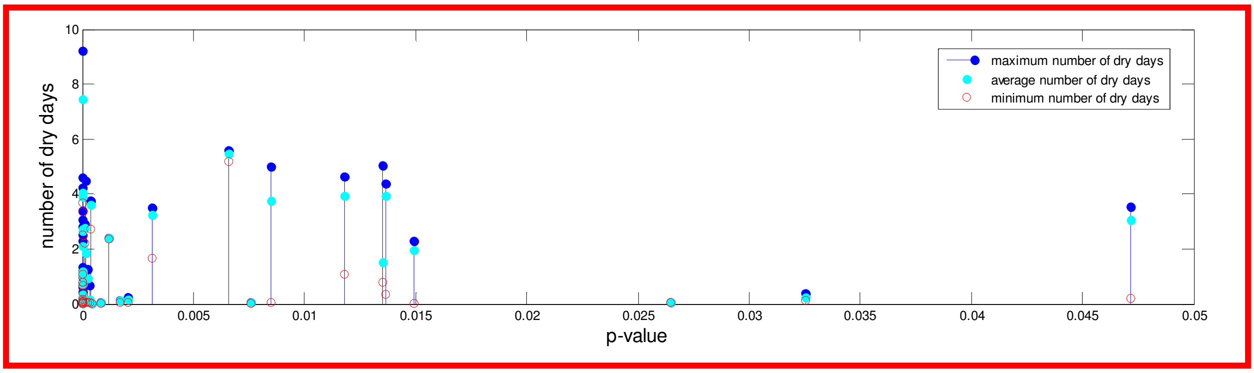


event nr.
number of stations retained [mm]
5
10
15
20
25
30
35
40
45
10
9
8
7
6
5
4
3
2
1
0

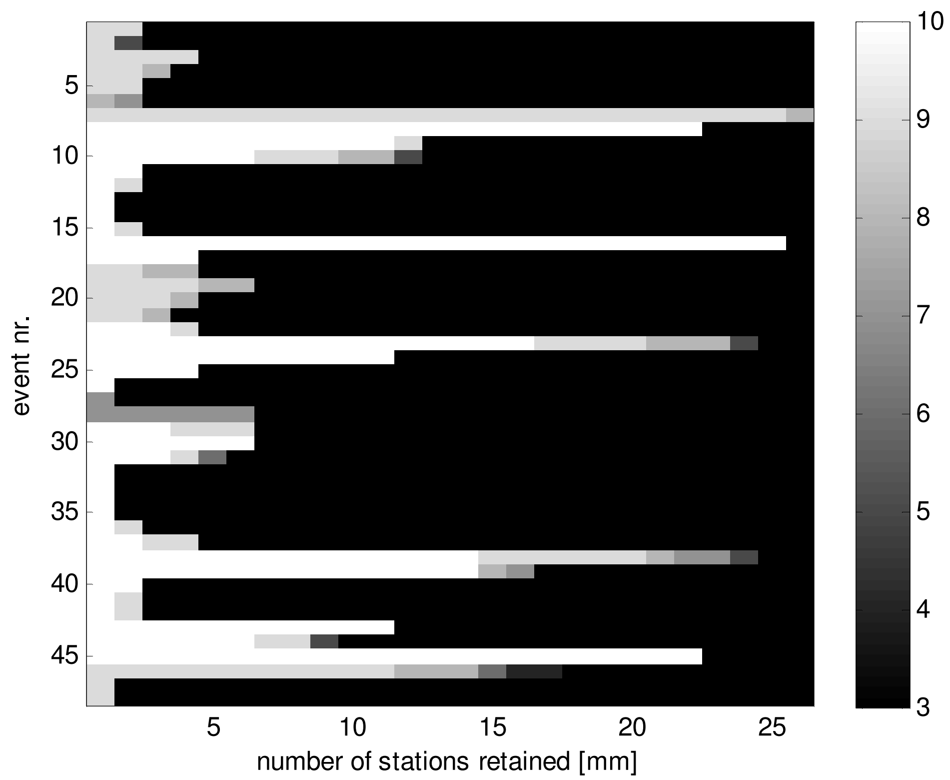


maximum number of dry days
average number of dry days
mininum number of dry days
p-value
Number of dry days before the event [mm]
p-value [-]
R coefficient



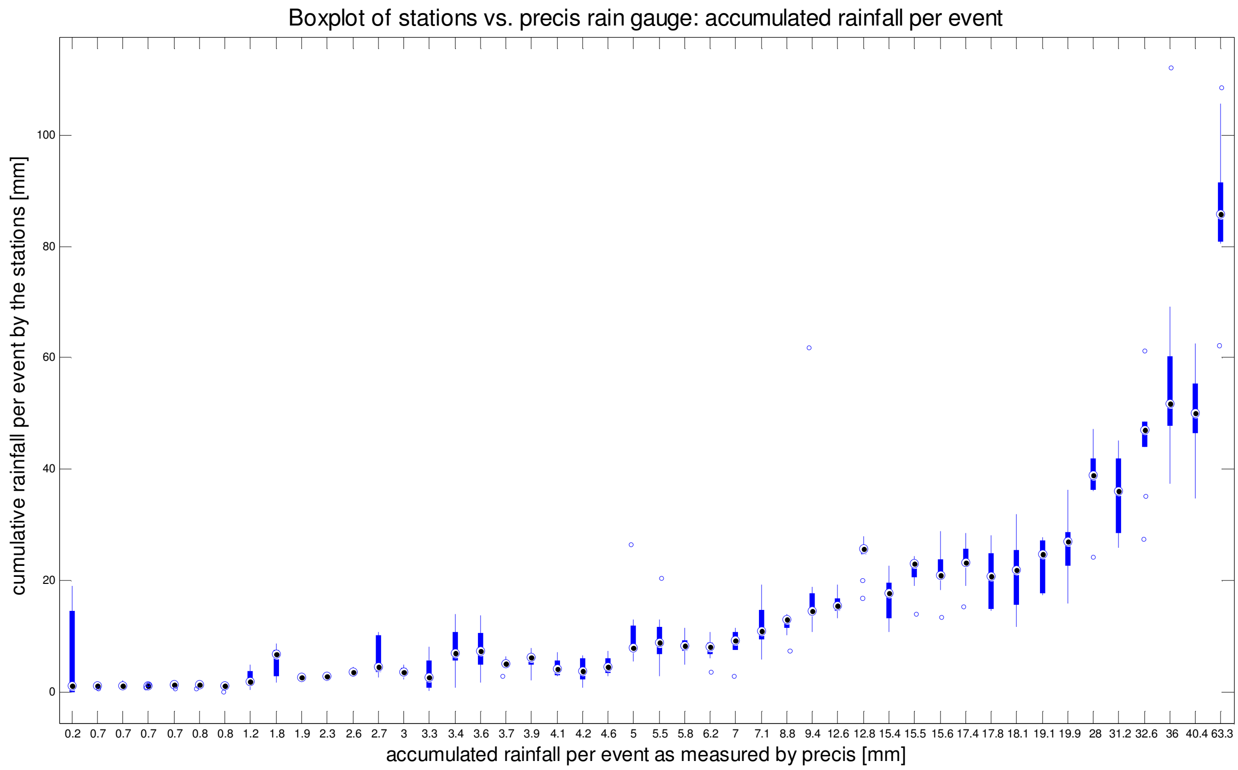


Comparison Hill-valley

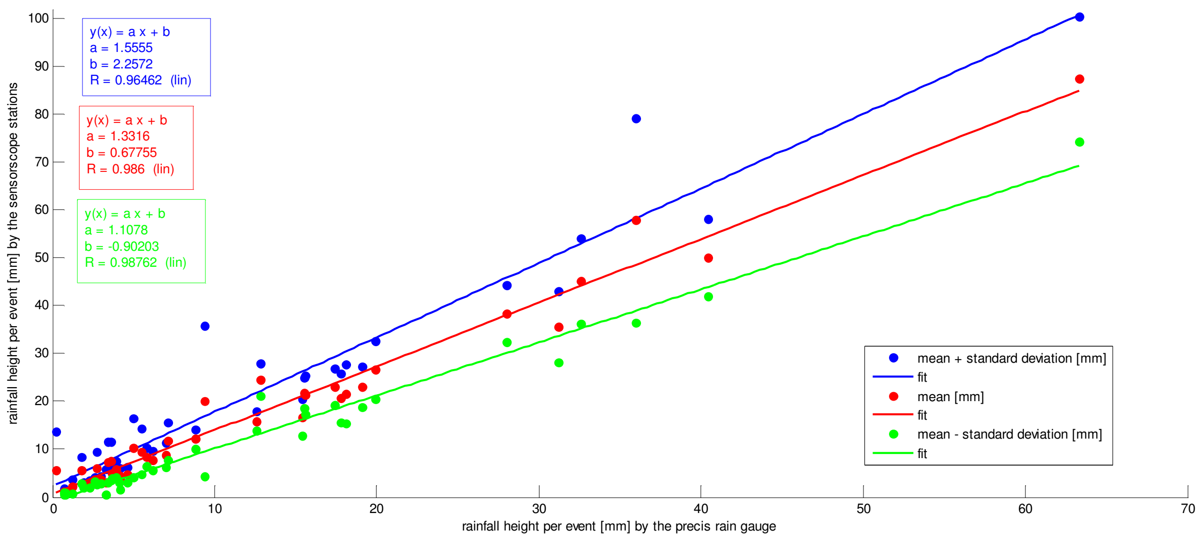


Graphs comparing the data of the précis rain gauge with the other stations

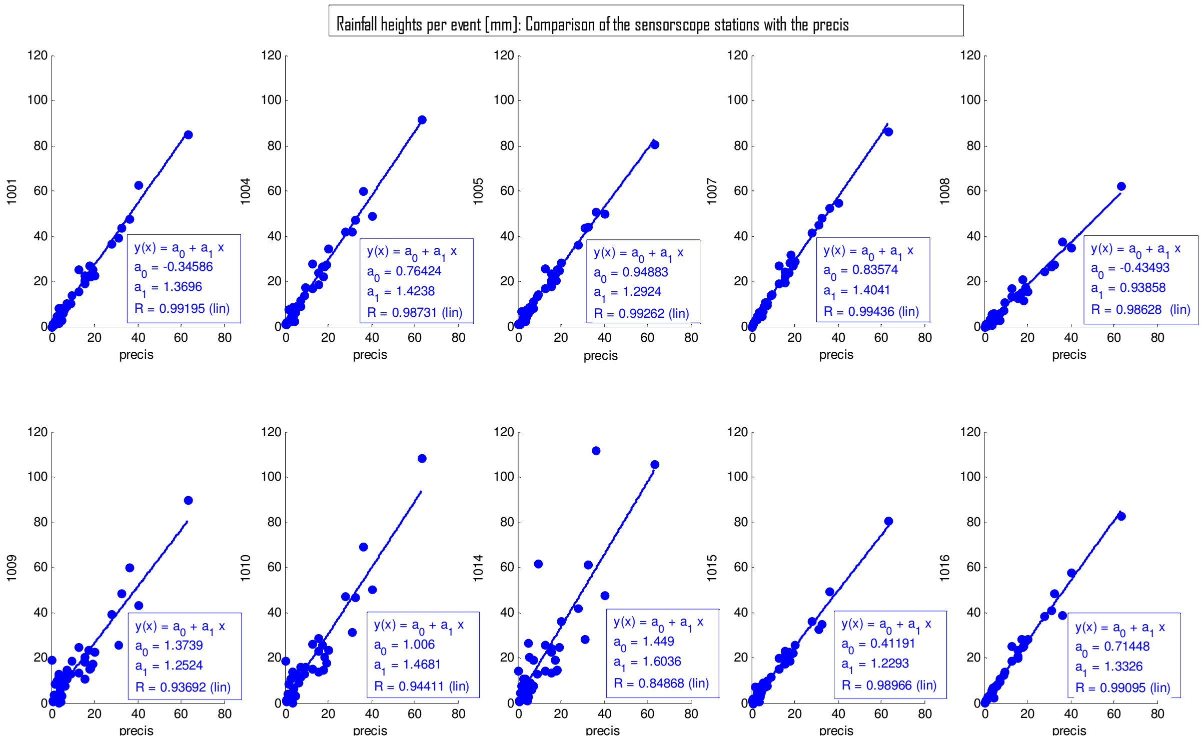
A.



B.



C.



Rainfall heights per event [mm]: Comparison of the sensorscope stations with the precis
1001
y(x) = a0 + a1 x
a0 = -0.34586
a1 = 1.3696
R = 0.99195 (lin)
1004
y(x) = a0 + a1 x
a0 = 0.76424
a1 = 1.4238
R = 0.98731 (lin)
1005
y(x) = a0 + a1 x
a0 = 0.94883
a1 = 1.2924
R = 0.99262 (lin)
1007
y(x) = a0 + a1 x
a0 = 0.83574
a1 = 1.4041
R = 0.99436 (lin)
1008
y(x) = a0 + a1 x
a0 = -0.43493
a1 = 0.93858
R = 0.98628 (lin)
1009
y(x) = a0 + a1 x
a0 = 1.3739
a1 = 1.2524
R = 0.93692 (lin)
1010
y(x) = a0 + a1 x
a0 = 1.006
a1 = 1.4681
R = 0.94411 (lin)
1014
y(x) = a0 + a1 x
a0 = 1.449
a1 = 1.6036
R = 0.84868 (lin)
1015
y(x) = a0 + a1 x
a0 = 0.41191
a1 = 1.2293
R = 0.98966 (lin)
1016
y(x) = a0 + a1 x
a0 = 0.71448
a1 = 1.3326
R = 0.99095 (lin)
precis