The influence of green roofs on the rainwater management system in an urban, tropical and undeveloped environment

Research Area
San Pedro Sula, Honduras

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Preface

This research has been done for my bachelor thesis of the study civil Engineering at the University of Twente, The Netherlands.

From April the 25th to July the 25th I lived in San Pedro Sula, Honduras, and did my research at the Plaza Comercial Bioclimática. The place commanded by the Architect A. Stassano is a good example of what can be done with green roofs. In her effort to enhance the further implementation of green roofs in the environment of San Pedro Sula, A. Stassano has built several green roofs and has carried out research regarding different aspects of green roofs. Last year a Dutch student Jitta Meijer did a research on the temperature effects of green roofs and as a follow up I was able to do a research on the subject of green roofs and rainwater management.

The research has not always been easy. A long time without precipitation and a political situation which forced me to leave the country for a week, made me creative and I approached the research question from a special point of view. After three months I found important insights regarding the water management capabilities of green roofs and I'm happy that I'm able to contribute to the efforts of A. Stassano in enhancing the implementation of green roofs into the environment of San Pedro Sula.

My special thanks go to A. Stassano for the opportunity which she gave me to do the research and for her help in finishing the investigation.

My thanks also go to ir. J.E. Avendano Castillo for being helpful in the preparation and correction of the report and his help in the arrangement of a good home address in San Pedro Sula.

At last I would like to thank Isaac Medina for his help in the preparation of the test setup and Jose Lopez, the local gardener, for helping me out in different situations and the effort he put in trying to improve my Spanish.

This research and stay in Honduras was an unique experience and I'm glad I had the opportunity to do it.

Herman van der Bent
August 2009

Summary

The main research question was if green roofs are a good design solution to improve the water management system in an urban, tropical and undeveloped environment. To answer this question the water management capacities of an inexpensive extensive green roof design have been examined in the tropical city of San Pedro Sula. Due to the fact of a short research period the investigation has been approached from a water balance point of view.

The boundary conditions tell us the total amount of water which can be handled by a green roof. For example the water handling capacity is about 32 mm of water for an extensive green roof with a 7.6 cm thick soil layer and the local used soil mix. This 32 mm of water is divided into three areas: The bottom capacity, the retention capacity and the drainage capacity. Out of these boundary conditions two main issues have been extracted.

1. The evaporation rate per day. This is the amount of water which leaves a green roof and therefore equals the retention capability when a new rain event approaches. The retention capability is limited by the fact that an aggressive irrigation strategy is used which waters the green roofs after one day without precipitation. The maximum amount of water which can be retained is therefore maximized by the evaporation rate of one day. This is about 5 mm of water. If a better plant type can be found which survives with a less frequent irrigation strategy the retention capacity can be a bit higher.
2. The second issue is the ability of green roofs to delay the discharge of water. This gives the sewer system more time to handle large amounts of precipitation. The boundary conditions maximize this drain capacity at 3.5 to 8 mm, depending on the size and slope of the roof. Half of this amount is delayed more than between 2 and 6 minutes depending on the slope of the roof. Other not examined configurations of green roofs leave space for different times of delay.

These rainwater management capacities have been compared to the precipitation data of ten years in San Pedro Sula. These data were organized in small, middle and heavy rain categories.

Small	0-20 mm/day	99 days per year
Middle	20-40 mm/day	12 days per year
Heavy	40 -200 mm/day	6 days per year

The influence of green roofs with their maximum of 5 mm retention and the ability to slow down 2 to 4 mm for 2 to 6 minutes is a positive number, but certainly on the heavy rain events the influence is limited. It should not be considered that green roofs can totally solve problems with the discharge of precipitation. A well maintained sewer system stays a governing design solution.

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1. Problem definition

Rain water management in an urban environment always is an issue which needs special attention. Rainwater is collected very quickly due to the fact that cities have lots of impermeable surfaces. With heavy precipitation this could lead to flooding of the streets with economical and social damage as a result.

This issue includes the place of research, San Pedro Sula, Honduras. Several news articles mentioned high amounts of precipitation in this city with a tropical climate. An example occurred on 24 October 2008. Large rainfalls caused the surroundings of San Pedro Sula to flood. 22.000 people had to be evacuated and 22 people lost their lives (Children International, 2008). To solve this water management problem several research directions are available. Some directions are to examine the flow of water in rivers, to do more research on the sewer systems or to explore possibilities to store rainwater in safe areas.

In Honduras an architect, A. Stassano, is convinced of the sustainable building theme. She is exploring the possibilities of sustainable building solutions to help the city forwards. Introducing green roofs as a profitable building concept is one of her issues.

Several studies mention the rainwater handling capabilities of green roofs. (Berghage R.D, 2009) (Mentens, et al., 2003) (Mentens, et al., 2005) Most of these studies did take place in developed countries with relative high financial means. This delivered data of the quality of green roofs and delivered some green roof concepts with high quality standards. The effect of green roofs on the rain water management system is found to be positive in these studies.

The two main interesting capabilities of green roofs to handle rainwater are the capability to retain a part of the rainwater and the second, to delay an amount of rainwater. Green roof are able to store rainwater in the soil layer and evaporate it back into the air. This retention factor will decrease the discharge of rainwater to the sewer system and therefore improve its performance. The capability of green roofs to delay an amount of water can help the sewer system to handle heavy rain events. The sewer system has more time to handle the rainwater, due to the slow release of rain water out of the green roofs. (Mentens, et al., 2003) (Van Woerd, 2005)

1.1 Research objective

This research has been done to find out if the water handling capacities of green roofs also contribute to a better rainwater management system in an urban, tropical and undeveloped environment.

Objective:

The main objective is formulated as follow:

> *To determine if green roofs are a good design solution to improve the rainwater management system in an urban, tropical and undeveloped environment.*

Terms explained:

Green roofs:

A roof design with a soil layer containing plants placed on top of the roof. The concept is explained in detail in chapter 2.

Rainwater management system:

The system which takes care of the discharges of rainwater from a city level to a river based level.

Urban environment:

In cities with high amounts of paved surfaces the rainwater is drained rapidly during a rain event.

Tropical environment:

Tropical environments have a typical distribution of rain events. The rain events in a tropical climate normally appear with high amounts of water and therefore their impact on the city environment is large. Therefore specific research is done on the precipitation characteristics of San Pedro Sula.

Undeveloped environment:

A large part of the city of San Pedro Sula is not highly developed. Therefore an inexpensive and simple green roofs design should be used. The financial means are scarce and need to be used wisely. This is considered in the designed test setup. The design is simple and relatively inexpensive.

Research questions

To fulfill the research objective three main questions have been answered:

1. What is the theoretical context of the green roofs concept?
2. How do the water handling capacities of green roofs work in a tropical and undeveloped environment?
3. What is the influence of green roofs on the urban water management system? (San Pedro Sula)

These questions are answered respectively in chapter 2, 3 and 4.

1.2 Research model

The research has the following setup to answer the main question if green roofs are a good design solution to improve the water management system in an urban, tropical and undeveloped environment. A test setup is used in the research phase on the water handling capacities. Because of the strong relationship with theory the test setup results are presented together with the describing theory.

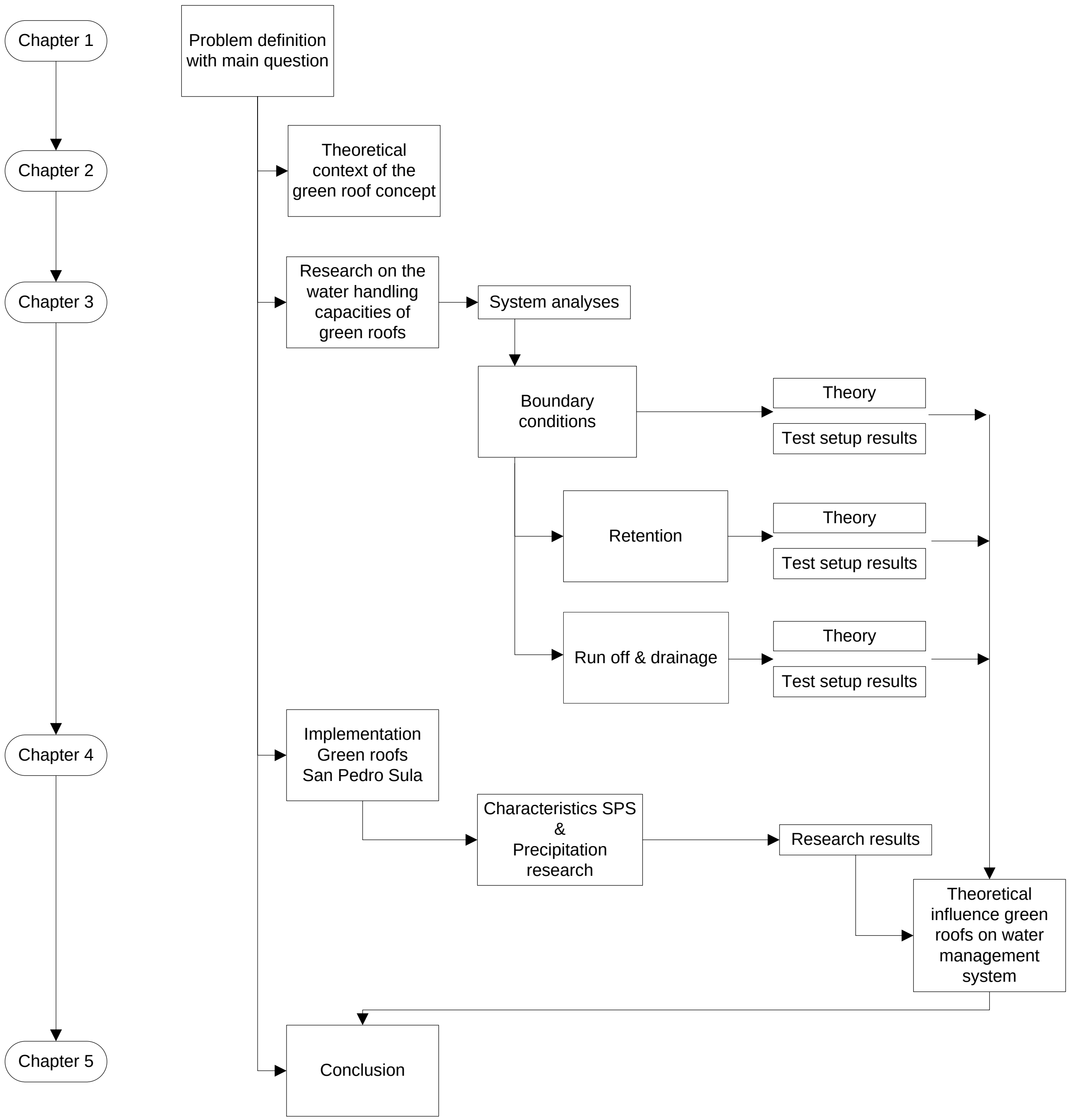


Figure 1 Research model

2. Context of the green roof concept

The green roof engineering concept uses the idea of using available space in the city as good as possible. The areas in the city we use unprofitable are the roofs on our buildings. The general idea is to place a substrate layer on top of roofs. It is possible for plants to grow in this substrate layer.

2.1 Functions of green roofs

A green roof is able to fulfill several functions at the same time.

The main functions of a green roof are:

1. To be the upper layer of a structural building and shield off an inside space.
2. To improve insulating capacities of a roof for better inside temperature conditions. It saves energy on cooling or heating and therefore creates a financial benefit for the owner. (Barrio, 1997) (Meijer, 2009)
3. To behave as a sun energy consumer. Plants use sun energy and reflect less heat into the air. This could lower outside temperatures. This effect is known as the urban-heat-island effect. (Meijer, 2009)
4. To act as a water retaining buffer. Decreasing the amount of impermeable surfaces in a city improves the water management performance. (Mentens, et al., 2005)
5. To improve the quality of esthetics in a city. A green environment will give people a good feeling. (Dunnet, et al., 2008)

All the different functions demand different designs of green roofs. From a water retaining and insulation point of view it is good for a green roof to have a thick substrate layer. On the other hand the weight should be as low as possible for just functioning as an upper layer of a construction, because in this way a smaller and more cost effective construction can be used. Mostly the demands of the owner of the building will determine the dimensions of a green roof and thereby how well it functions in each of the categories.

2.2 Extensive & Intensive Green roofs

To be able to classify different types of green roofs a distinction is made between extensive green roofs and intensive green roofs. Intensive green roofs have a thick substrate layer so bigger plants will be able to grow in it. The roof acts like a garden and needs maintenance. An extensive green roof needs far less maintenance and could be a sedum or a thin soil layer with grass or groundcovers. (Mentens, et al., 2003)

Figure 3 Example intensive green roof

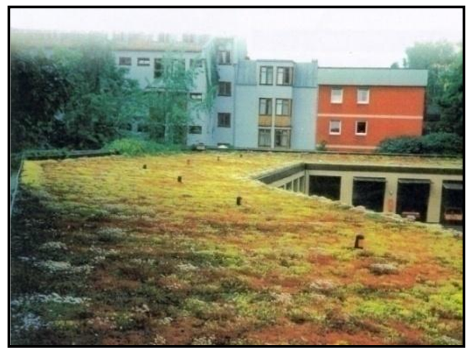


Figure 2 Example extensive green roof

Intensive green roofs

An intensive green roof acts as a real garden on top of a roof and has therefore more opportunities for esthetic appearances. Also due to the thicker soil layer an intensive green roof has slightly better performances on acting as an insulation layer and as a buffer for precipitation. Nevertheless it has a large disadvantage on just functioning as the structural top layer of a building. A well designed structural plan is needed to support an intensive green roof. This will increase the costs of a building and also can be inconvenient when placing a green roof on existing buildings. Also can be considered that maintaining an intensive green roof will take its necessary costs.

Extensive green roofs

In contrary with intensive green roofs, extensive green roofs do not acquire an extended structural plan. They can be placed on most roofs, because of a relatively low weight. The costs for an extensive green roof will be lower compared to intensive green roofs and also less maintenance is required. The esthetics of an extensive green roof have boundaries because of the thickness of the soil layer. It is not possible to plant trees, but different types of sedum, grass, ground covers and small plants survive on extensive green roofs.

2.3 Design parameters

Green roofs can appear in a wide variety. It is up to the owner and the architect to choose between different options. Options to be chosen out are: the slope of the roof, the orientation of the roof, the buildup of the soil, the thickness of the soil layer, the presence of a drain layer, the used plant type and the installed irrigation system. All these parameters have an influence on the water handling capabilities of green roofs.

Besides the parameters which can be influenced by the design, also the period of the year with different weather conditions and the intensity of a rain event influence the capabilities of a green roof to handle precipitation.

The design parameters which influence the water handling capacities of green roofs are discussed in the chapters were the parameters have an influence. This can be in the area of the boundary conditions, the retention theory or the drainage theory.

Construction layers

A green roof consists of several construction layers. A typical build up of a green roof consists out of the following layers:

- Construction layer
- Insulation layer
- Waterproof layer
- Root membrane
- Drainage layer
- Growing medium
- Plants
- Drainage system

A full description of these construction layers can be found in the report: (Meijer, 2009)

The insulation layer, the drainage layer and a drainage system appear in sophisticated green roof designs. The architect A. Stassano has been doing some tests with the layers on the Plaza Comercial Bioclimática, but for cost effective reasons these were not added to the test setup used for the research on the water handling capacities. (Chapter 3)

3. Research: Water handling capacities of green roofs

The water handling capacities of green roofs are analyzed to answer the main question if green roofs can improve the rainwater management system in an urban, tropical and undeveloped environment.

3.1 Research methodology

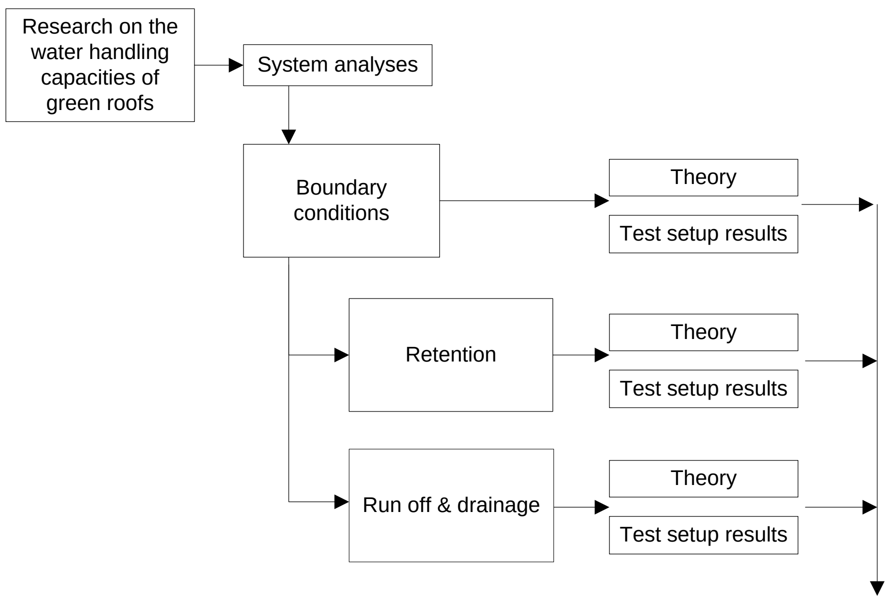


Figure 4 Research model: Section field study

The analyses of the water handling capacities of green roofs start in the next paragraph with a system approach on the water content balance of a green roof. After this system approach the water handling capacities are further limited by the boundary conditions. The theory and the test setup results are presented in the same paragraph. This makes it easier to explain.

After the boundary conditions, the retention of rainwater is discussed. From a balance point of view the evapotranspiration in time is responsible for the capacity of green roofs to retain water. In this chapter a model for the estimation of the evapotranspiration is discussed and results of evaporation rates of the test setup are evaluated. The irrigation strategy appears to have a big influence on the retention capacity of green roofs. Also on this subject the theory and the test setup results are presented in the same paragraph.

The capacity of green roofs to delay a certain part of rainwater drained to the sewer system is discussed. Boundary conditions give a first limit on how much water can be delayed and drainage rates give an idea of time of delay. The slope has a big influence on the drainage velocity and thereby on the effectiveness of green roofs to delay rainwater in time.

That makes the setup of the discussion of the water handling capacities as follow:

1. System approach: Gives the water balances
2. Boundary conditions: Gives boundaries of capacities
3. Retention: Given by the evaporation rate in time
4. Runoff and drainage: Gives time delays in run off

The different design parameters which have an influence on the three describing factors of green roof (the boundary conditions, the evaporation rate and the drainage) are discussed in the report if they have an influence on the specific water handling capacity. For the different aspect the design parameters are discussed as follow:

1. The boundary conditions
   (Soil thickness, soil build up, plant type, slope)
2. The retention
   (Plant type, slope, orientation, irrigation, year period)
3. The runoff and drainage
   (Slope, soil build up, drainage layer, intensity rain event)

Research constrains

A test setup was made to deliver good data of the water handling capacities of green roofs. Some decisions had to be made in order to build a good setup which was able to deliver sufficient data, but for a reasonable price.

The first decision had to be made on the build up and proportions of the test green roofs. Because the research question is focused on a research area with an undeveloped environment the choice for an inexpensive extensive green roof was made. The chosen build up for the test green roofs is visualized with pictures in Appendix A.

The second decision was made on the different design parameters which were closely examined. In consultation with the architect A. Stassano was decided to make a more detailed investigating of the influence of the soil thickness and the slope of the roof on the water handling capacities of green roofs. The influence of a drainage layer is not investigated because of a limited amount of available building material and due to the fact that a drainage layer will increase the costs of a green roof and therefore it is less easy to implement in an undeveloped environment. The used soil type is decided to be the soil mix the architect uses for green roofs. This is a mixture of soil and gravel. This soil layer is planted with a grass layer so it will not take a lot of time to fully cover the roof.

Test setup

Out of the research constrains the decision was made to make four equally sized green roofs of one square meter. The decision was made in comprehension with the supervising architect.

Figure 5 Test setup first research part

Figure 6 Test setup second research part

Two of the green roofs had a soil thickness of 5.1 cm and two green roofs had a soil thickness of 7.6 cm. These sizes were chosen to cover a wide area of extensive green roofs.

The axe between the four roofs was placed in a east west configuration. This assured that the sun had an equal amount of radiation on every green roof.

During the first month the test roofs were placed under an angle of 2 degrees, so the first month there was an equal pare of roofs. Of as well the equal pare of 5.1 cm roofs and the equal pare of 7.6 cm roofs the data were compared, so an estimation could be made of the differences between two supposedly the same green roofs. The differences in research results between the two sets of roof were on average 2-3%, with a standard deviation of another 3-4%. These numbers are reasonable. A full comparison is made in the data report.

After a month of research the roofs were placed under a slope to examine the influence of the slope on the water handling capacities of green roofs.

Tests

The data of the tests done on the green roofs are noted in the data report. De tests on the evapotranspiration part were done by adding water in a saturating level. The difference between input and output of water is the evapotranspiration (Eq 5). The tests done on the drainage research part were done by measuring the ouput of water after saturation of the green roof. After every certain time period (minutes) the output was measured. Then the drainage graphs were made and compared with an aproximation line. The graphs and tables can be found in the data report. Concluding data is presented in the upcoming paragraphs.

3.2 System Approach

In the system approach the water balances for long time and short time periods are given. These are the setup for the investigation and give a general understanding of the water handling capacities.

Water Balance - long time period

For longer time periods (months – years) the water content of green roofs is a balance between water going in and water going out. From time to time the water content can differ, but on a large time scale it has no net storage. The water balance for green roofs on a long time scale looks as follows:

$$Water_{in} = Water_{out} \qquad \text{(Eq. 1)}$$

Water going in a green roof is always Precipitation or Irrigation. The water going out is always the sum of Runoff or Evapotranspiration. (Mentens, et al., 2003) There is no other way for water to enter or leave a green roof. Therefore the water balance can be written as follow:

$$I \cdot \Delta t + P \cdot \Delta t = R \cdot \Delta t + ET \cdot \Delta t \qquad \text{(Eq. 2)}$$

With:

$I \cdot \Delta t$	Irrigation during the time period
$P \cdot \Delta t$	Precipitation during the time period
$R \cdot \Delta t$	Run off during the time period
$ET \cdot \Delta t$	Evapotranspiration during the time period

Water Balance - Short time period

For short time periods (hours – days) the capability of green roofs to store water cannot be neglected. Two types of occurrence can be examined. One during a rain event (or irrigation) and one in the absent of rain events. The balance for a rain event is as follow:

$$P \cdot \Delta t = R \cdot \Delta t + \Delta W_p \cdot \Delta t + (\Delta ET \cdot \Delta t) \qquad \text{(Eq. 3)}$$

$P \cdot \Delta t$	Precipitation during time period
$R \cdot \Delta t$	Runoff during time period
$\Delta W_p \cdot \Delta t$	Change water content level due to precipitation during time period
$(\Delta ET \cdot \Delta t)$	Evapotranspiration during time period (Considered to be neglectable during rain events)

Therefore the change in water content level after a rain event is:

$$\Delta W_p \cdot \Delta t = (P - R) \cdot \Delta t \qquad \text{(Eq. 4)}$$

The other event for short time periods is in the absence of rain events. During these time periods only Evapotranspiration will take place. The water which leaves the roof comes directly out of the water storage. Therefore change in water content level is:

$$\Delta W_e \cdot \Delta t = ET \cdot \Delta t \qquad \text{(Eq. 5)}$$

$\Delta ET \cdot \Delta t$	Evapotranspiration during time period
$\Delta W_e \cdot \Delta t$	Change water content level due to evapotranspiration during time period

Water content level in time

The water content of a green roof is influenced by the two balances mentioned above: one during rain events (or irrigation) and one in the absence of rain events.

$$\Delta W_p \cdot \Delta t = (P - R) \cdot \Delta t \quad \& \quad \Delta W_e \cdot \Delta t = ET \cdot \Delta t \qquad \text{(Eq. 4 \& Eq.5)}$$

The water content level in time can then be described by the equation:

$$\Delta W \cdot \Delta t = (P - R) \cdot \Delta t + ET \cdot \Delta t \qquad \text{(Eq. 6)}$$

To visualize what is happening with the water content in time an example of the progress in time is presented in the next graph. Notify certain limits of the possible water content of a green roof.

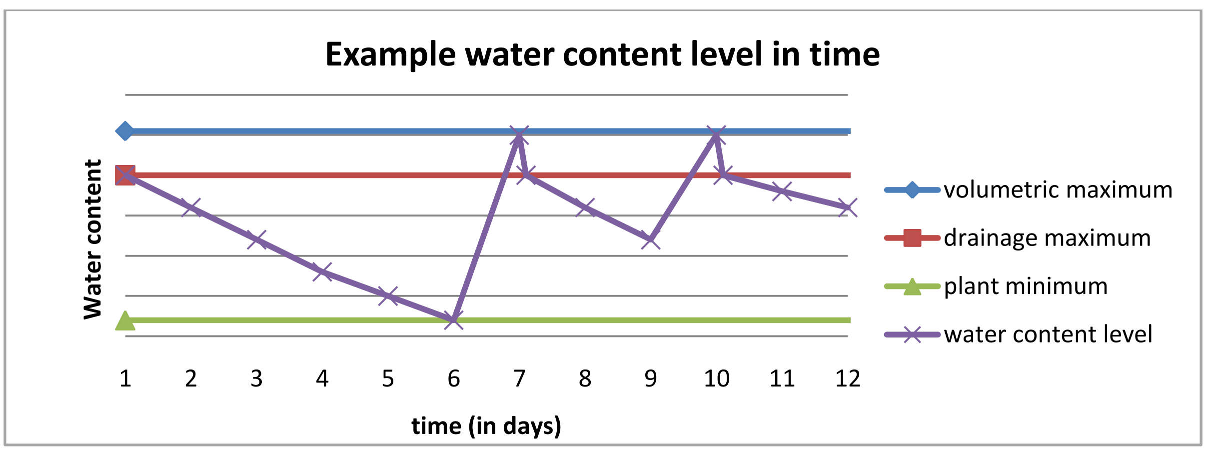


Figure 7 Example water content level in time

Explanation:

Day 1-5	no precipitation, evaporation and transpiration (no irrigation)
Day 6	heavy rainfall, water content high, after rain back to drainage maximum
Day 7-9	no precipitation, evaporation and transpiration
Day 9	no precipitation, irrigation
Day 10-12	no precipitation, evaporation and transpiration

3.3 Boundary conditions

The water contents mentioned in the "example water content in time" always behaves between certain limits. These limits are different for different types of green roofs.

Volumetric maximum

The maximum water content level appears if a green roof is fully saturated. In nature this will never occur, because of the possibility to drain water at the bottom. The maximum water content of a green roof is determined by its soil buildup. The volumetric maximum per square meter is dependent from the thickness of the total soil layer and its porosity. The porosity differs with different types of soil. (Budhu, 2000)

$$W_{\max} = H * n \quad \text{(Eq. 7)}$$

With:

$W_{\max}$	Maximum water content level in mm
H	Thickness of the soil layer in mm
n	Porosity

Drainage maximum

The drainage maximum is the maximum of water a green roof can hold with the possibility to drain rainwater at the bottom. The water which stays in the roof is trapped due to capillary forces. The water what drips out comes out due to gravity forces. After every rainfall the water content of a green roof will at least drop under this drainage maximum. The drainage maximum of a green roof is dependent from the type of soil, its permeability and the slope of the roof.

Plant minimum

The last boundary limit is at which water content level a plant starts to wither. The water content level of a green roof should never be below this level, because else the plants will start to die. The plant minimum is dependent for the type of plant used.

Typical water content, earth and agriculture science

From earth and agriculture science typical ranges for water contents are available. (Rawls W.J, 1982) investigated several typical water contents in America. Typical data are described in the table below. One remark is that in earth and agriculture science the field capacity is measured. This is a drainage maximum for soil three days after a rainfall. The drainage maximum for a green roof is measured right after a rainfall and will always be slightly higher.

Name	Typical water content	Description
Volumetric maximum	0.35 to 0.5 * Thickness	Fully saturated water, eq to effective porosity
Drainage maximum	0.1 to 0.4 * Thickness	Soil moisture at 0.33 Pa tension
Plant minimum	0.01 to 0.25 * Thickness	Minimum soil moisture at which a plant wilts

Figure 8 Table typical water contents of soil

Boundary capacities

The boundary limits are the ends of the boundary capacities of water content in green roofs. With the limits boundary capacities can easily be determined. The boundary capacities are water contents in liters per square meter or, equally, mm of water.

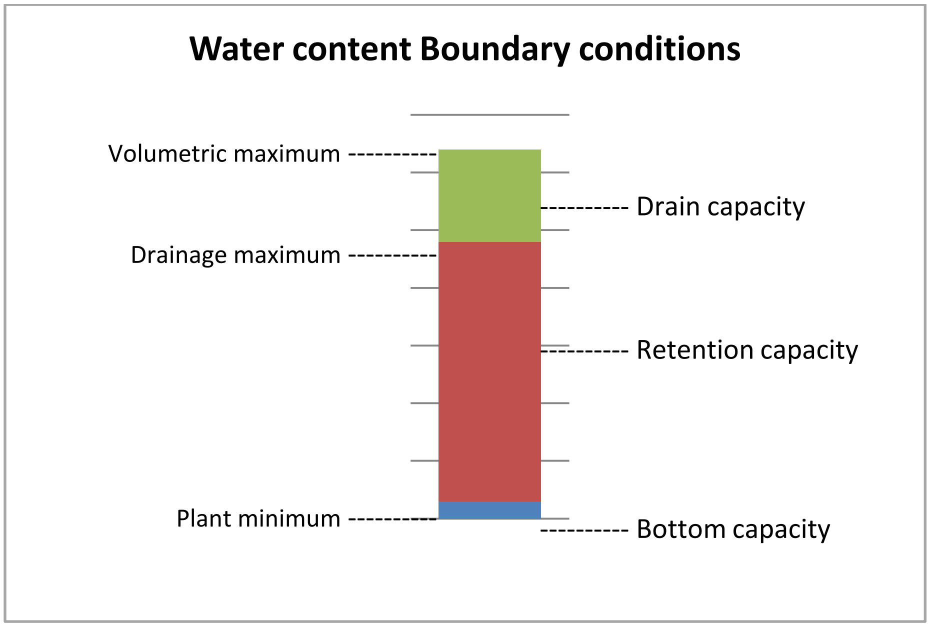


Figure 9 Water content Boundary conditions

Drain capacity

Total capacity of green roof to drain (and delay) rainwater. Water will drain from the roof if gravity forces are stronger than capillary forces. The drainage maximum is reached when these forces become equal. In nature green roofs will never reach their volumetric maximum. This is depended from the intensity of a rain event. This means that not the whole theoretical drain capacity is used and therefore an effective drain capacity is introduced in chapter 2.4, where the drainage part is discussed in detail.

Retention capacity

No more water will drain from a green roof if after a rain event the drainage maximum water content level is reached. After that the evapotranspiration starts. Water will evaporate and makes space for water to be retained in future rain events. This evapotranspiration process can take several days. However irrigation strategies have a big impact on how much space can be cleared for retention of future rain events.

Bottom capacity

At a certain water content plants are not able to extract water and will start to wilt. Capillary forces are too big for plants to extract water.

Research Results: Water content Boundary conditions

Actual research has been done on extensive green roofs. As mentioned in the research decisions two influencing factors are examined in detail. The soil thickness and the roof slope have been examined at the far ends of their boundaries. In consultation with the architect was decided that extensive green roofs build in the area of San Pedro Sula will probably have soil thicknesses between 2 and 3 inches. However in the report the metric system will be used and therefore the thicknesses are converted to 5.1 cm and 7.6 cm. The roof slopes will have dimensions somewhere between 2 and 20 degrees. This is because of discharge and erosion reasons. In total this makes that the research boundaries of the two influencing factors are:

Soil thickness	5.1 cm	&	7.6 cm
Roof slope	2 degree	&	20 degree

The research results on the boundary conditions: the volumetric maximum, the drainage maximum and the plant minimum are presented in the table below. Also the drain capacity, Retention capacity and Bottom capacity are calculated. The results are presented in liters per square meter and this equals mm of precipitation. On the next page a graph is published for better understanding.

7,6 cm soil - 2 degree slope					5.1 cm soil - 2 degree slope			
	Wc %	Boundary (l/m2)	Capacity (l/m2)			Wc %	Boundary (l/m2)	Capacity (l/m2)
Volumetric maximum	43%	32,6			Volumetric maximum	43%	23,9	
Drain capacity			8,6		Drain capacity			6,3
Drainage maximum	32%	24,0			Drainage maximum	32%	17,6	
Retention capacity			22,5		Retention capacity			16,5
Wilting minimum	2%	1,5			Wilting minimum	2%	1,1	
Bottom capacity			1,5		Bottom capacity			1,1

7.6 cm soil - 20 degree slope					5,1 cm soil - 20 degree slope			
	Wc %	Boundary (l/m2)	Capacity (l/m2)			Wc %	Boundary (l/m2)	Capacity (l/m2)
Volumetric maximum	43%	32,6			Volumetric maximum	43%	23,9	
Drain capacity			12,3		Drain capacity			9,0
Drainage maximum	27%	20,3			Drainage maximum	27%	14,9	
Retention capacity			18,8		Retention capacity			13,8
Wilting minimum	2%	1,5			Wilting minimum	2%	1,1	
Bottom capacity			1,5		Bottom capacity			1,1

Figure 10 Table: Test setup results boundary conditions

The volumetric maximum has been determined with a full saturated test which determines the porosity. The porosity of the tested green roofs is determined to be 0.43. Information on this test is found in the data report. With the total thickness of the soil layer (5.1 and 7.6 cm) the volumetric maximum is determined.

The drainage maximum is determined in different tests on evaporation and drainage rates. Research data can be found in the data report. The drainage maximum is a rough estimation and is different for sloped roofs.

The wilting minimum is determined with literature and is taken to be 2%. This is because to measure this wilting minimum a part of the green roof has to be taken apart and this would influence further measurements. Special equipment was not available. The wilting minimum has not a big influence on the water handling capacities, because it is a good assumption that in general a green roofs will not reach this point due to irrigation.

The determined water content boundary conditions for the four test roofs are presented in the graph:

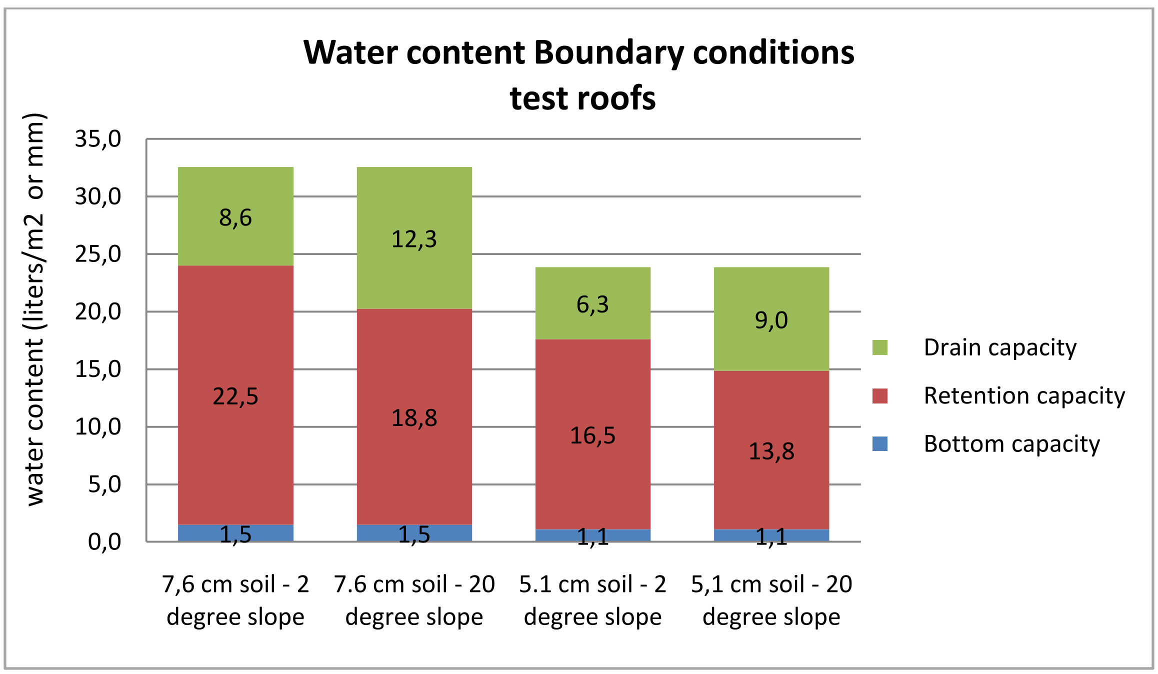


Figure 11 Graph: Test setup results boundary conditions

It is clear that the 7.6 cm soils have a higher volumetric maximum. Thereby they have a higher retention capacity and drain capacity as the 5.1 cm soils. When a roof is placed under a slope the retention capacity drops a bit. This is because there is a slightly higher head of water. For sloped roofs is in theory the drain capacity higher, but the effective used drain capacity is lower. This is explained in paragraph 2.4.

Influence of design parameters

Soil thickness

The soil thickness has a direct influence on the boundary conditions. An increased soil thickness increases the volumetric maximum (Eq. 7) and thereby increases the maximum drain capacity and the maximum retention capacity as well.

Soil buildup

The soil build up, and mainly its porosity has a direct influence on the boundary conditions. However the architect uses always a soil mixture with sand and gravel. There will be not a big difference in the porosity. The porosities of soil is general between 0.35 and 0.5. (Rawls W.J, 1982) Therefore the influence of the porosity is quite limited.

Plant type

The choice of plant type will have a small influence on the boundary conditions of green roofs. Different plants have different wilting boundaries (water content needed to survive.)

Slope

The slope of the roof has a small influence on the boundary conditions of the roof. A roof with a higher slope (examined 20 degree) has a little higher water pressure and thereby the roof is able to hold a bit less water than an almost flat roof. The volumetric maximum in comparison is the same. But the retention capacity for a sloped roof is lower.

Conclusion boundary conditions

For extensive green roofs with soil layers up to 7.6 cm of soil the boundary conditions have an upper limit of about 32 liters water per square meter. This volumetric maximum decreases with lower soil thickness and lower porosities. The maximum water content is divided into three areas: the drainage capacity, the retention capacity and the bottom capacity. The amounts for the four examined green roofs are presented in the following graph:

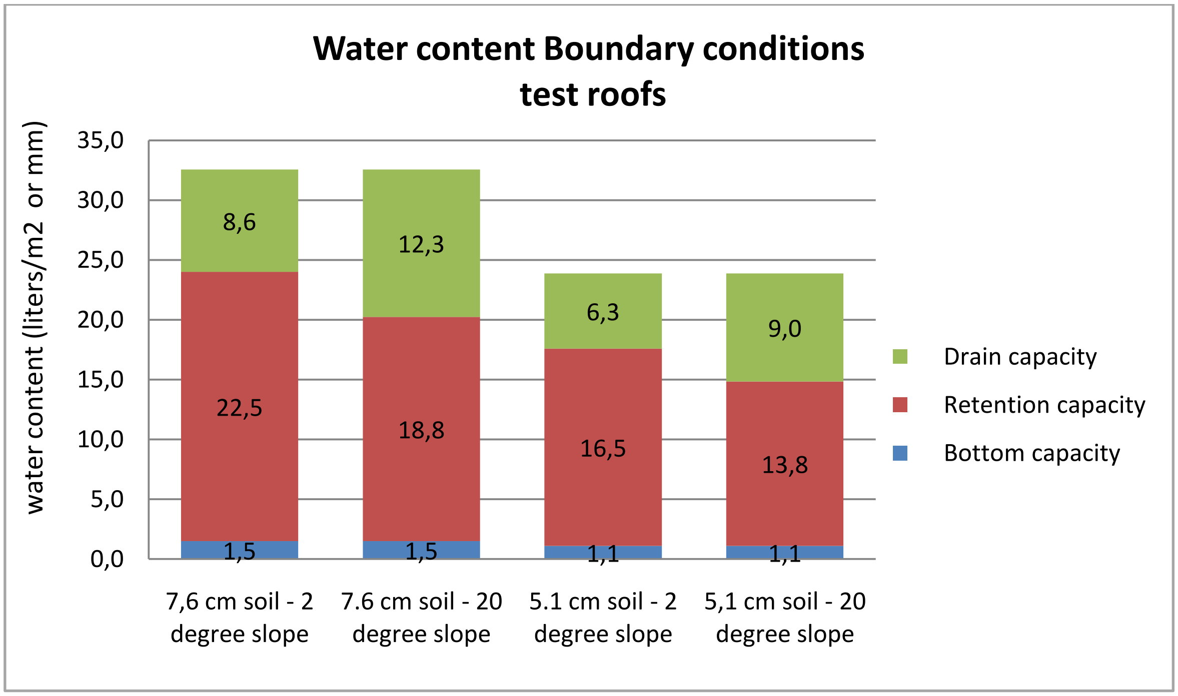


Figure 12 Graph: Test setup results boundary conditions

A part of the retention capacity will be used for the retention of rain water due to evapotranspiration. This is explained in paragraph 2.3. A part of the drainage capacity will be used for a delay in discharge to the sewer system. This is explained in the drainage paragraph 2.4.

3.4 Retention

Retention equals evapotranspiration

After a rain event the water content level is assumed to be at the drainage maximum. After that the water starts evaporating until the next rain event. The capacity to retain rainwater is determined by the water which is evaporated in time. This because the water content balances (eq. 4 & eq. 5) from chapter 2.1 have to be equal.

Evapotranspiration model of Hargreaves (long term)

A popular equation to describe evapotranspiration (evaporation + transpiration) is the Penman-Monteith equation. (ASCE, 1996) However to use the penman-monteith equation detailed temperature data are required. Another simplified version of the penman-monteith equation is the equation of Hargreaves. It uses daily average temperatures to describe a model for the evapotranspiration. This empirical model is a normal used model to predict evapotranspiration. (Allen, 2006) The equation of Hargreaves looks as follow: (ASCE, 1996)

$$ET = K_c \cdot ET_0 \qquad \text{(eq. 8)}$$

In this equation the evapotranspiration is described by a reference evapotranspiration ET_0 and a crop coefficient K_c which is depended from the used type of vegetation.

The reference evapotranspiration is described by the following equation:

$$ET_0 = 0.0023 \cdot (T_{\max} - T_{\min})^{0.5} \cdot (T_{mean} + 17.8)(R_A) \qquad \text{(Eq. 9)}$$

With:

T_{max} Maximum daily temperature
T_{min} Minimum daily temperature
T_{mean} Mean daily temperature
R_a Sun radiation in MJ/m^2/d

In this equation the reference evapotranspiration is calculated by determining the total amount of incoming sun radiation R_A and the influence of temperature differences during day time.

The total amount of sun radiation is different for every other location in the world. The total amount of sun radiation in MJ/m^2/d is calculated with the following equation:

$$R_A = \frac{24 \cdot 60}{\pi} G_k d_r \left[\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)\right] \quad \text{(Eq. 10)}$$

With:

$$\delta = 0.4093 \sin\left(2\pi \frac{(283 + J)}{365}\right) \quad \text{(Eq. 11)}$$

&

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right) \quad \text{(Eq. 12)}$$

&

$$\omega_s = \arccos\left[-\tan(\phi)\tan(\delta)\right] \quad \text{(Eq. 13)}$$

With:

R_A	Sun radiation in MJ /m^2/d
G_k	Solar constant (4.92 MJ/m^2/d)
d_r	Inverse distance factor earth-sun
ω_r	Sunset hour angle in radians
ϕ	Latitude in radians
δ	Solar declination in radians
J	Day of the year

For the city of San Pedro Sula (Latitude: 15.27°) the sun radiation during a year is presented in the following graph:

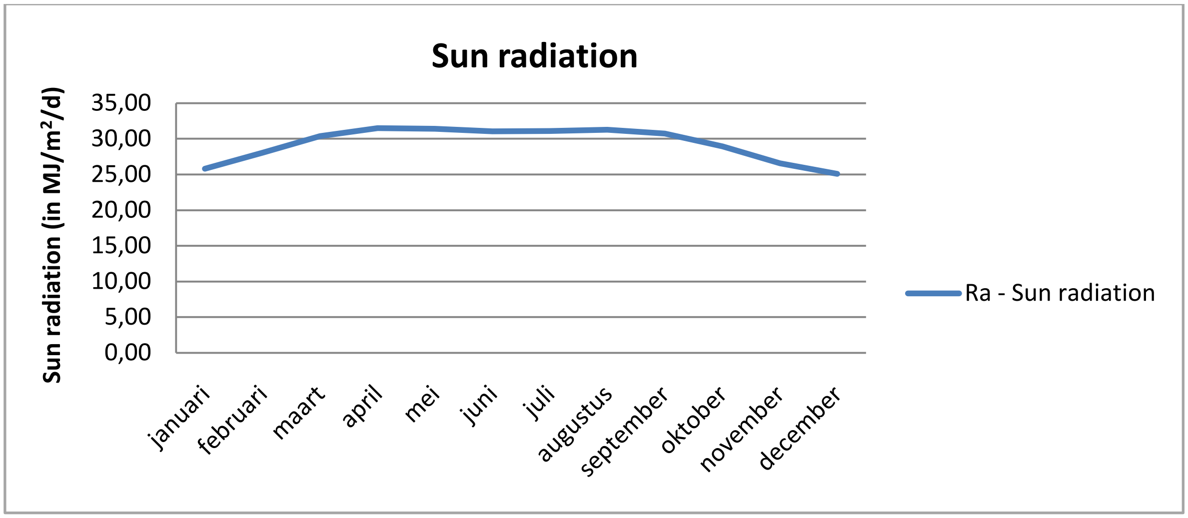


Figure 13 Graph: annual sun radiation SPS

With these data of sun radiation and the maximum and minimum temperature differences the reference evapotranspiration can be determined by using equation 9.

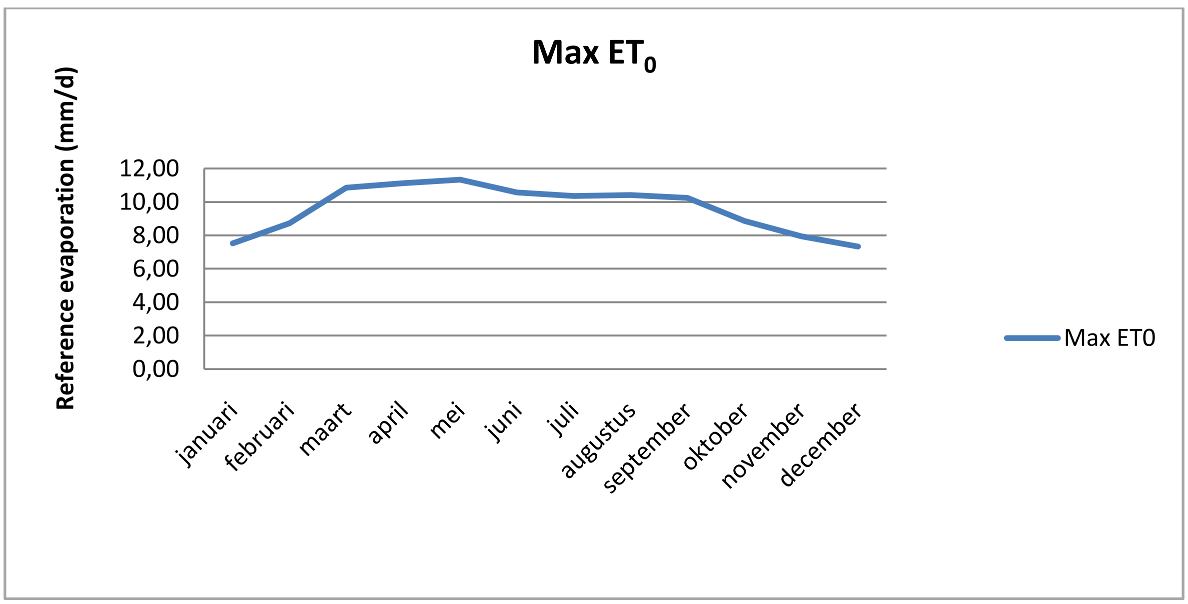


Figure 14 Graph: Annual maximum Evapotranspiration SPS

Minimum and maximum temperatures are used from a worldwide weather station, Allmetsat, to determine the Maximum reference evapotranspiration. (Allmetsat, 2009) Data can be found in the data report.

The crop coefficient K_c in the formula of Hargreaves is empirically determined for lots of different plant types. A few are noted in the following table. More K_c coefficients can be found in the hydrology handbook for civil engineers, page 186. (ASCE, 1996)

Description	Kc1	Kc2
Grass pasture, rotation	0,40	0,85
Grass Pasture, poor manage	0,30	0,75
Open water	1,05	1,05

Figure 15 Crop coefficients

K_{c1}=General factor under unfrequented soil wetting
K_{c2}=Sub humid climate, average wind speed

For grass this factor is between 0.30 in the early stage of growth and with fully grown condition the K_c can be as high as 0.75. These lines are drawn in the graph.

Following the equation the evaporation rates are between 2 and 8 liters per square meter per day for grass as vegetation, dependent on the day of the year and the development of the vegetation.

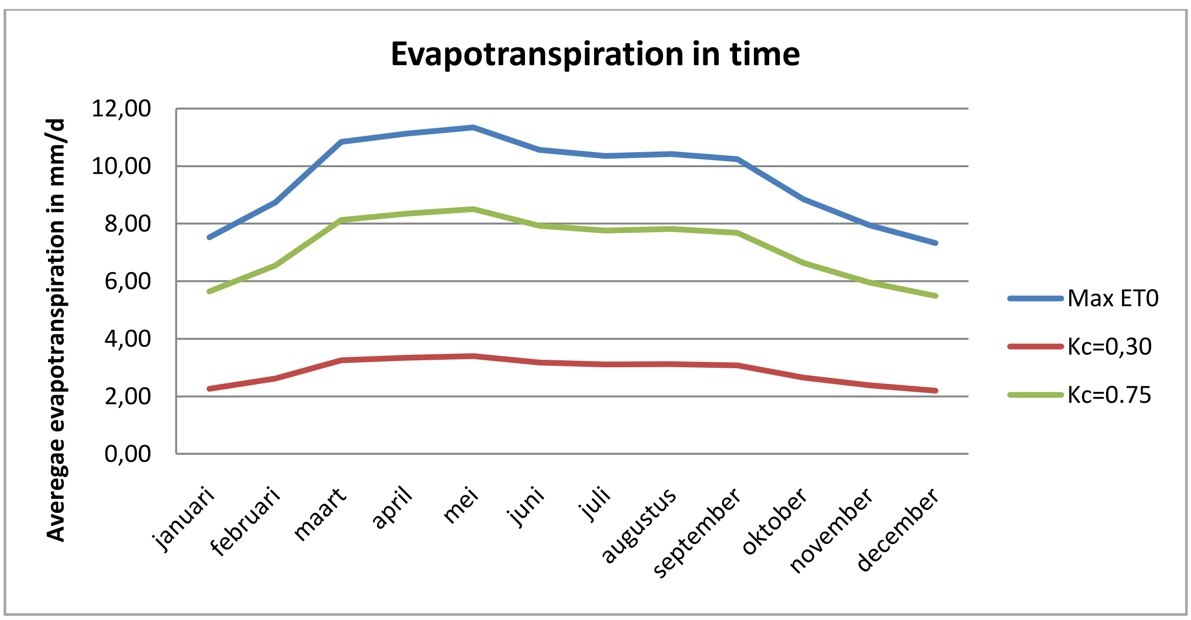


Figure 16 Graph Evapotranspiration SPS with crop coefficient factors

Research Results Evapotranspiration (long term)

During a month measurements have been taken on the evaporation rates of the 5.1 and 7.6 cm test roofs. The roofs where placed in two sets with a two degree slope.

After a certain amount of time the retention of rainwater was measured. This was done by fully saturating the roof and measure the difference in irrigation and run off. From equation 5 this equals the evaporation rate in time.

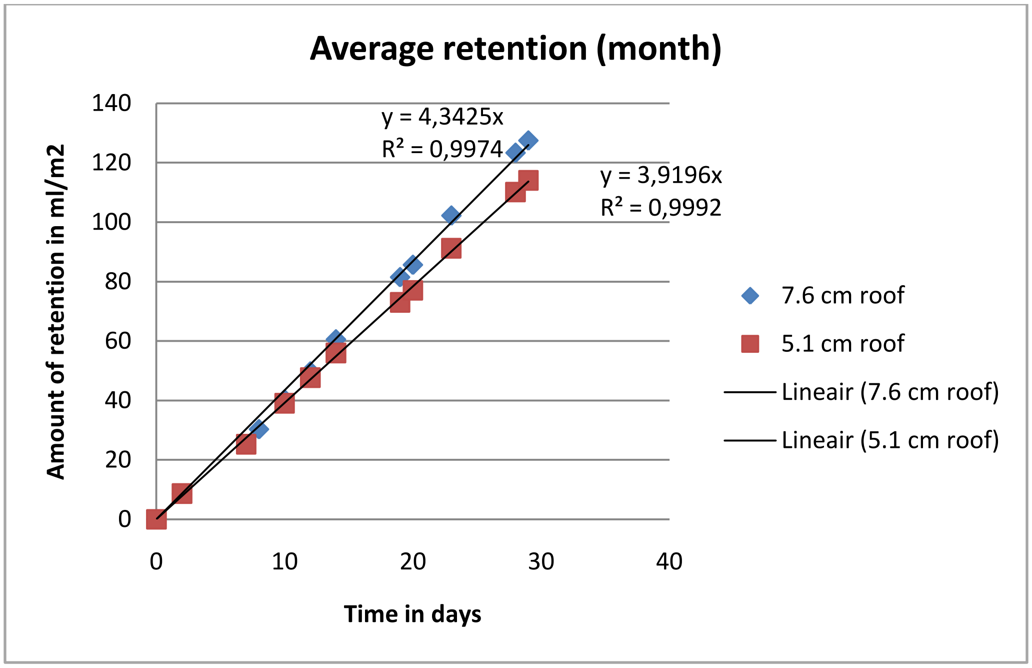


Figure 17 Average retention test setup

A trend line is added and so the average evapotranspiration rate for the two degree roofs can be determined.

7.6 cm soil	4.3 liters per square meter per day
5.1 cm soil	3.9 liters per square meter per day

The difference between the 2 and 3 inch roofs is due to lower evaporation rates on a daily bases when there is a low amount of water present in the roof. This effect is explained in the next paragraph.

The evaporation rates were determined during the 18 May to 17 June with average day temperatures between 30 and 35 degrees. During these days there was no actual rainfall. All the additional water was provided by the researcher himself.

Combining the evaporation theory of Hargreaves with the actual measured evaporation rates delivers the next graph.

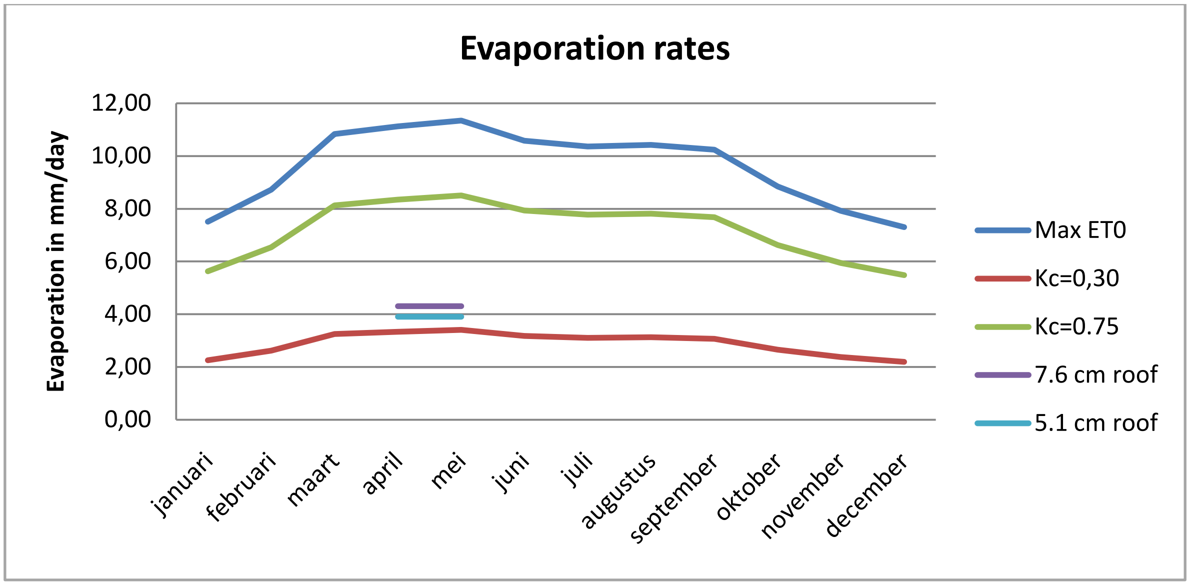


Figure 18 Evaporation rater Theory of Hargreaves combined with test setup results

The theoretical rates seem to be a bit high, although the green roofs where starting in their growing phase and suffered some growing difficulties due to some tests under wilting conditions.

Evapotranspiration model (short term)

Another model for describing evapotranspiration rates on a short timescale is discussed in the hydrology handbook for civil engineers. This evaporation model gives a closer look on the evaporation on a short time scale. (ASCE, 1996)

The model explains that water on soil evaporates in two stages. The first stage is water which stays after a rain event on top of the soil layer or in the leaves of vegetation. This water is evaporated very quickly because there are no capilary or molucalair forces to hold the water. In stage two water starts to evaporate at a certain rate. When less water is available for evaporation the capilary and moleculaire forces hold the water much stronger so the evaporationrate drops in time.

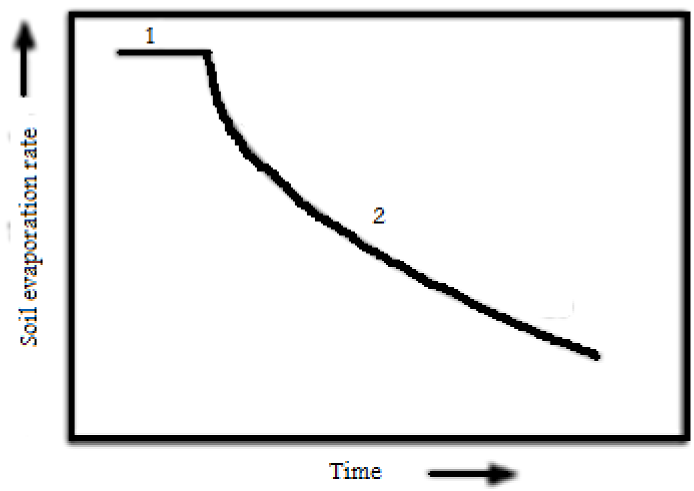


Figure 19 Short time evapotranspiration model

Research Results Evapotranspiration (short term)

This short term evaporation effect is examined for the 7.6 and 5.1 cm roofs under a 2.0 degree slope.

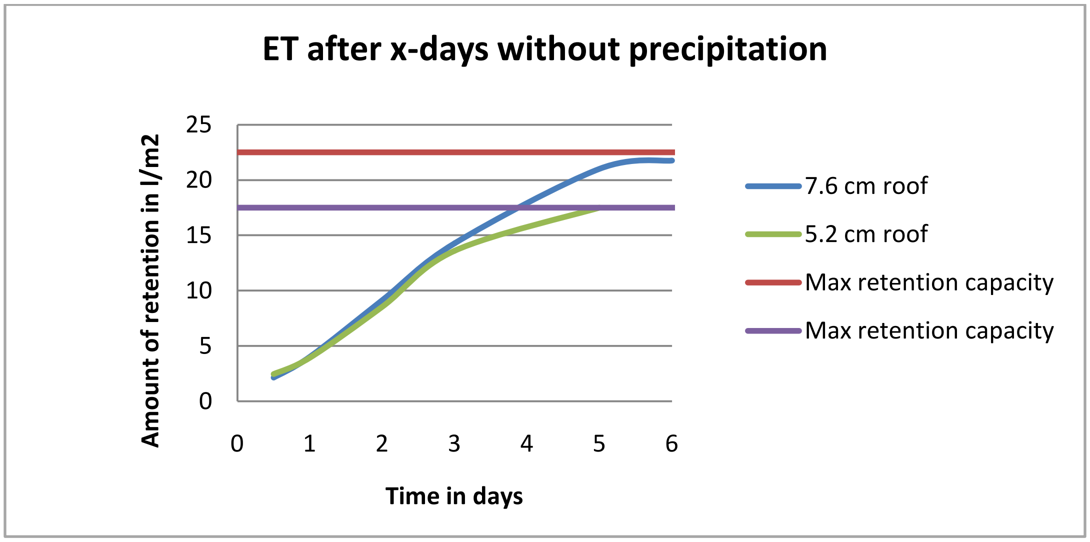


Figure 20 Evapotranspiration after x-days without precipitation

The results are presented as the possible amount of retention after a certain amount of days. The evaporation rate discussed on the previous page is the curve of the line. The first stage evaporation could not be identified. After the first few hours the line is quite steep and therefore the evapotranspiration is high. After a few days the line gets less steep and therefore the evaporation rate drops in time.

It is shown that in the beginning the rates for the 5.1 and 7.6 cm roofs are more or less the same. After day three the two inch roof starts to have more trouble evaporating water, so the evaporation rate drops. After day five the plants start to whither and the 5.1 cm roof reaches its wilting boundary condition. (Chapter 2.2) For the 6.7 inch roofs it takes about a day longer to evapotranspirate the whole retention capacity.

The mean evaporation rate for the first three days is more or less 5.0 liters per square meter per day. This is a bit higher than the evaporation rate with the long term condition due to the fact that the long term evaporation measurements include some data of evaporation after 3 to 6 days without precipitation.

The data of this research part are added in the data report.

Irrigation strategy

The irrigation strategy is a very important factor in the determination of the capability of green roofs to retain rainwater.

Due to high temperatures and long periods without precipitation all the build green roofs in San Pedro Sula should have an irrigation system.

Three different types of irrigation strategies can be recognized.

1. Aggressive — Every day without precipitation irrigation takes place.
2. Adaptive — Only when it is necessary for plants irrigation takes place.
3. None — Poorly maintained roof, plants will die.

At the research site a number of green roofs is installed and they have irrigation systems installed. The irrigations strategy to maintain the green roofs is aggressive. Irrigation takes place every day without precipitation. This makes that the green roofs always have a lot of water in them and the water content always is close to the drainage maximum. A red block is added in the evaporation/retention graph presented in the previous chapter to show in which area the evaporation rates (and thereby retention capacity) will be. This is about 5 mm of water after one day.

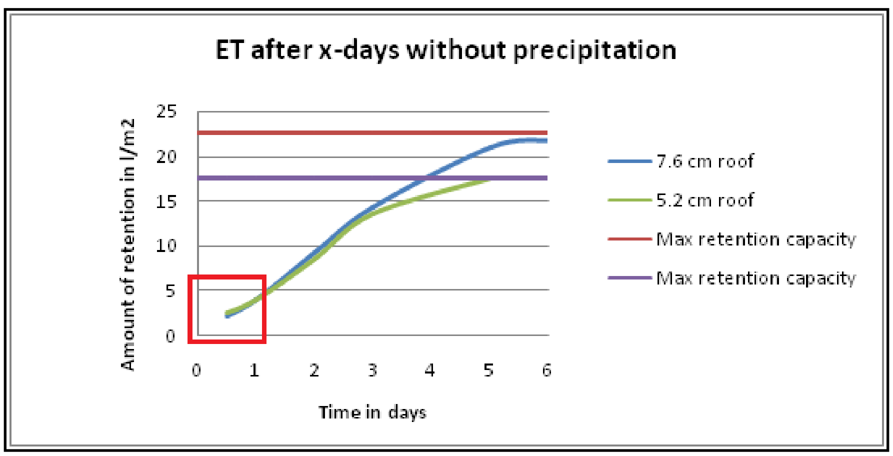


Figure 21 Evapotranspiration after x-days without precipitation with irrigation strategy

Also if precipitation comes day after day the capacity of green roofs to retain water will just act like it is irrigated every day and thereby has a retention capacity of more or less 5 liters per square meter per day as well.

With an adaptive irrigation strategy green roofs could have a higher capacity of retention, but it could prove to be more difficult for plants to grow. The none irrigation strategy is taken to not take place. Effects will be kind of the same as with an adaptive strategy, but it is not likely that plants will survive during dry periods.

Other influencing parameters Evapotranspiration

Soil thickness

An increased soil thickness increases the retention capacity and so it will take longer to evapotranspirated the whole retention capacity and thereby longer for plants to reach the wilting point. An increased soil thickness has not directly an influence on better retention capabilities. This is because it only increases the time to evapotranspirate all the water, but not the evapotranspiration rate. A thicker soil layer could make that it is not necessary to have an aggressive irrigation strategy and use a more adaptive strategy. This could indirectly increase the water retaining capacities.

Plant type

The choice of plant type has a direct influence on the evapotranspiration rate. This is explained with the formula of Hargreaves. Investigations by the ASCE give different values of K_c-factors. A small list is added in Appendix B. In general plants with large surface areas of leaves make a plant transpirate more water, but will give more shadow to the soil, so soil evaporation will decrease. (ASCE, 1996)

Slope

The slope has an influence on the evapotranspiration rate in combination with the orientation.

Orientation

The orientation of a green roof, north, east, south, west has an influence on the evapotranspiration rate due to the fact that more or less sun radiation is captured by the roof. This only has an effect on sloped roofs; flat roofs do not really have an orientation. In area's around the equator the sun goes during the day from east to west in a perfect line and has not really a north or south orientation (small seasonable effect) Roofs directed to the north and south take thereby full sun al day. (Test setup configuration) Orientations to the east and west have less sunlight in the evening or respectively in the morning. This has an effect on the evaporation rate. A research done in Belgium shows that the influence of the orientation could be substantial, but they conclude that more research is necessary to give valid results. (Mentens, et al., 2003)

Year period

The period of the year has an influence on the evapotranspiration capabilities of green roofs. On countries around the equator the amount of sun radiation during a year does not change that much. The reliability of green roof in equator areas will there for be higher than in more northern or southern areas. During the year period there are (sometimes large) differences in amounts of precipitation. Also rain events quick after each other have an influence on the time to evaporate water in between and thereby on the retention capabilities.

Retention conclusion

Retention capacities of green roofs are highly dependent of the evaporation rate and the irrigation strategy which is used. Research results show that the evaporation rate for the grass covered green roofs is about 5 liters per square meter per day in the first three days after a precipitation. This is equal for as well the green roofs with a soil thickness of 7.6 and 5.1 cm.

Green roofs with other plant types will have different evapotranspiration rates, but they will be in same order of amounts.

Because of a frequently used aggressive irrigations strategy which waters the green roofs to their drainage maximum every day without precipitation the expected retaining capacity is equal to be the same as the evaporation rate on one day. This is about 5 liters per square meter per day and equals a precipitation of 5 mm.

3.5 Run off & drainage

During a rain event runoff water leaves the roof in two ways, Direct Runoff and Drainage. In most of the research done on green roofs no differential is made between the two types. This is because it is hard to measure the difference between the actual runoff and drainage, but there are some things to say about the runoff and drainage.

- First, direct runoff of water is more likely to cause erosion on the top layer of the soil.
- Second, drainage of rainwater will extend the period of time of water drainage to the sewer system and could thereby be preferable.

The reason why normally no distinction is made between the direct runoff and drainage is the high amount of factors which influence the distinction between the two types. Factors which can be examined are the slope, type of soil, type of plant and the thickness of the soil, but other parameters like the spread of plants on a green roof and the appearance of little drain paths inside a green roof will influence the distinction that much, that it is impossible to make up a full analytical model. With existing theories of drainage through soils it is possible to give some boundaries for the amount of drainage of rainwater after a rainfall or peak rain event.

*An extra model on the forecasting of runoff, the curvenumber method is added in appendix B. This is for the more experienced reader.

Drain capacity

The maximum amount of water which can be drained and leave the roof after a rain event or heavy precipitation peak is maximized by the difference between the volumetric maximum and the drainage maximum per square meter. (chapter 3.1) This is called the drain capacity. The drain capacity in liters per square meter or mm precipitation for the 5.1 and 7.6cm soils are:

	7.6 cm soil	5.1 cm soil
2 degree slope	8.6	6.3
20 degree slope	12.3	9.0

Figure 22 Drain capacity green roofs

However this drainage capacity is never fully used because in nature the roof will drain water during a rain event. The effective used drain capacity is simulated with heavy precipitation rates by the researcher. For the 2 degree roofs the simulated maximum is about 80 to 90% percent of the total drain volume. For the 20 degree roofs this is only about 40% (because direct run off start to appear). The effective volumetric drain capacity is presented in the next table in (l/m2):

	7.6 cm soil	5.1 cm soil
Eff. 2 degree slope	7.0	6.3
Eff. 20 degree slope	4.0	3.3

Figure 23 Effective drain capacity green roofs

Drainage theory

The theory on the drainage part of the green roofs starts with the general law which describes the volume rate of flow through an homogenous body of soil, the law of Darcy (Budhu, 2000):

$$Q = A \cdot \frac{k}{n} \cdot \frac{\Delta H}{l} \tag{Eq. 14}$$

Where:

Q	volume rate of flow
A	cross-sectional area
k	coefficient of permeability
n	porosity
H	head
l	drain length

This equation is valid for large homogeneous bodies of soil fully filled with water. The soil layer on top of a green roof is not homogeneous due to small drainage paths in the layer and in time the water content decrease due to the volume rate of flow out of the green roof. Therefore this equation is not directly applicable, but it can be taken that the cross-sectional area, the coefficient of permeability, the porosity and the drain length will not change in time during the drainage of water after a rain event. The Volume Rate is then only depended on the total head of water (ΔH) in the green roof. This Head is related to the total amount of drainage water in the roof. Therefore the head will decrease in time due to water leaving the roof.

It is possible to describe the relationship of the total amount of water in the green roof which has to be in time with an equation, because of the direct relation between the total head and the volume rate of flow (The head decreases due to an volume rate of flow in time).

Equation:

$$\Delta D_w(t) = \frac{D_{ws}}{2^{t/hvt}} \tag{Eq.15}$$

Where:

$\Delta D_w(t)$	Amount of drain water in a green roof at a certain time in l/m^2
D_{ws}	Amount of drain water at the start in l/m^2. (Maximized by the boundary conditions)
t	Time in minutes
HVT	Half Value Time in minutes

The maximum amount of drain water which can be drained is maximized by the (effective) boundary conditions of green roofs. This is simulated by the amount of drain water at the start D_{ws} . If there is more water is on a green roof this will leave the roof as direct run off. The ability of green roofs to use this drain capacity is dependent from the intensity of a rain event.

An example is given in the following graph. At the start of the drainage part there is an amount of drain water present in the roof. This is dependent from the intensity of the rain event, but will never exceed the effective drain capacity mentioned in the paragraph above. In this example two different amounts of water which could occur are chosen. They are more or less the maximum effective capacities for a roof under a two degree slope and a roof under a twenty degree slope as mentioned in the paragraph above.

In the example graph also the influence of the Half Value Time is visible. The half value time is the time it takes to half an amount of water and can be found by doing experiments. A roof with a high HVT takes more time to slow down all the effective drain water which is in the roof at the start of the drainage period. A roof with a low HVT drains the drain water much faster. For a half value time of 6 minutes for a 2 degree roof this means that after 6 minutes 50% of the drainage water has left the green roof. After another 6 minutes another 50% from the remaining drain water has left. This means that after 12 minutes 75% has left. And so on. With an HVT of 2 minutes 75% of the drain water has left after 4 minutes.

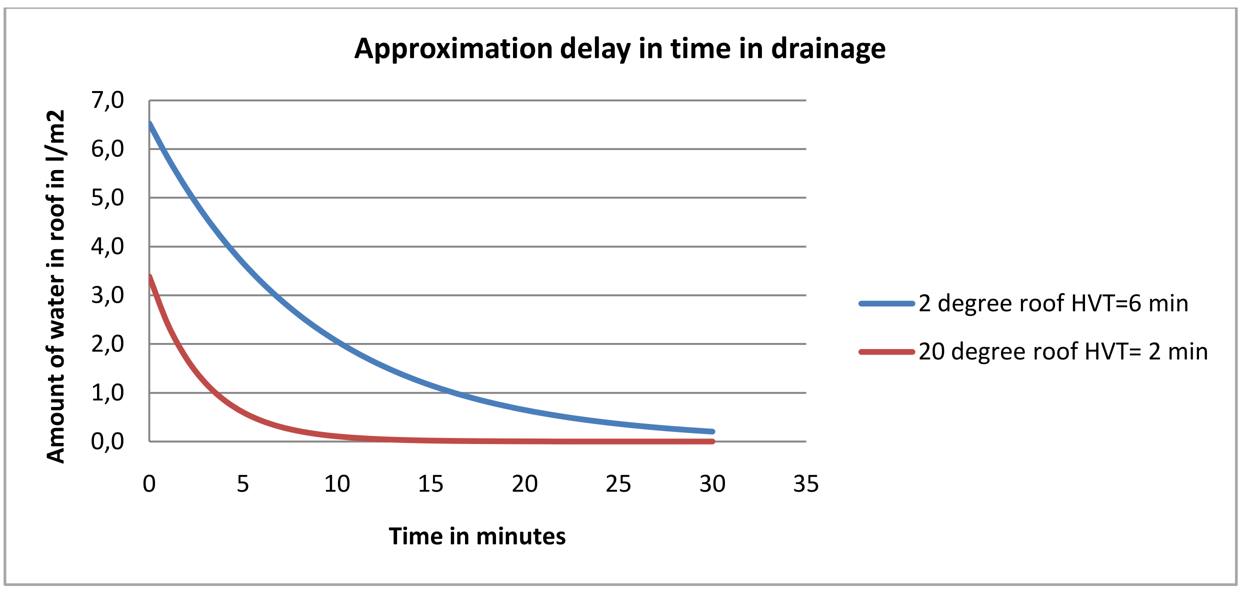


Figure 24 Approximation delay in time in drainage

The half value times are different for different types of green roofs and the slope of the roof has a big influence in the capacity to slow down the drainage of rain water in time. In the next chapter with the test results is shown that for the tested roof slopes the HVT are indeed 2 and 6 minutes.

Research results drainage, time delay

On the test roofs the drainage of water after a simulated rain event was measured. The graphs show the amount of water which is in the roof. In time the curve gets les steep which means the water leaves the roof with a lower velocity of flow. Every set of results has another line added: the approximation (APP). The theory on the water which is drained after a certain period of time is explained in the paragraph above together with an explanation for the approximation line.

The test results of the two degree slope are presented in the two following graphs, the half value time for both approximation lines are six minutes:

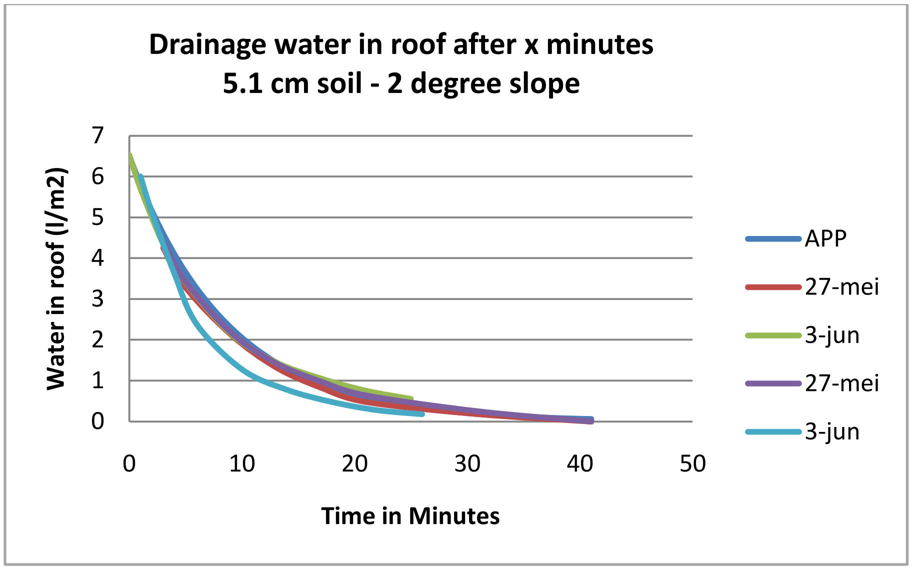


Figure 25 Drain water in roofs after x-minutes 5.1 cm soil - 2 degree slope

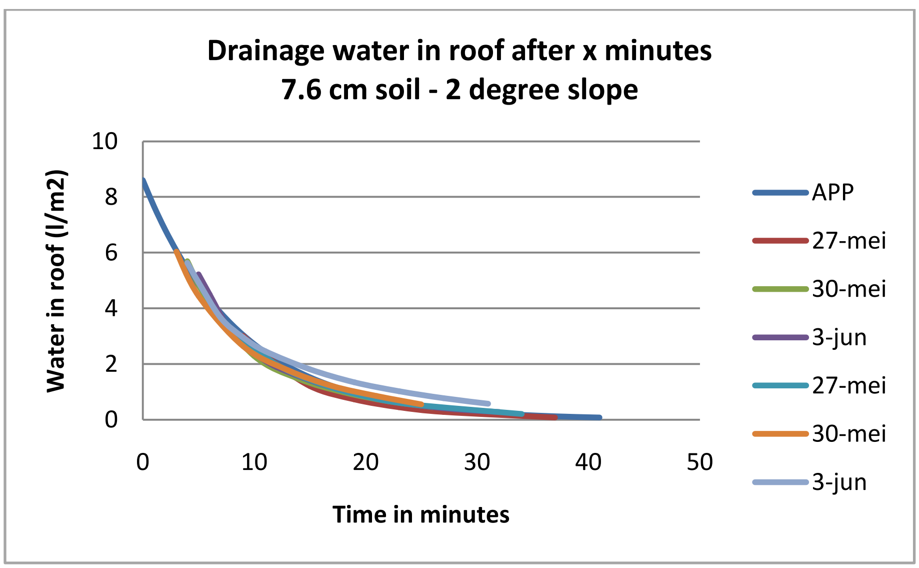


Figure 26 Drain water in roofs after x-minutes 7.6 cm soil - 2 degree slope

The test results of the twenty degree slope are presented in the next graphs, the half value time for both approximation lines are two minutes:

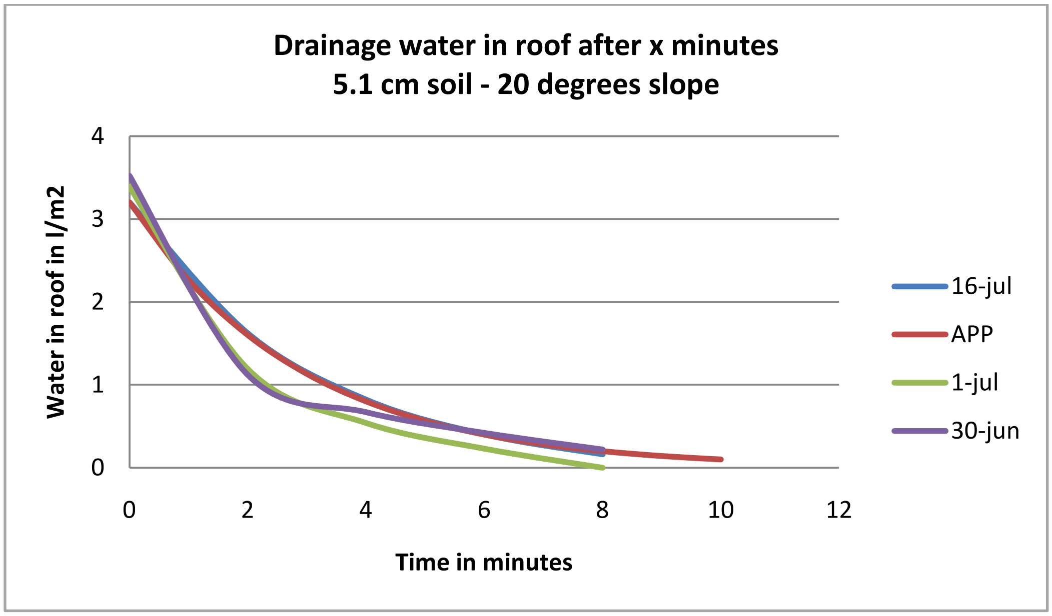


Figure 27 Drain water in roofs after x-minutes 5.1 cm soil - 20 degree slope

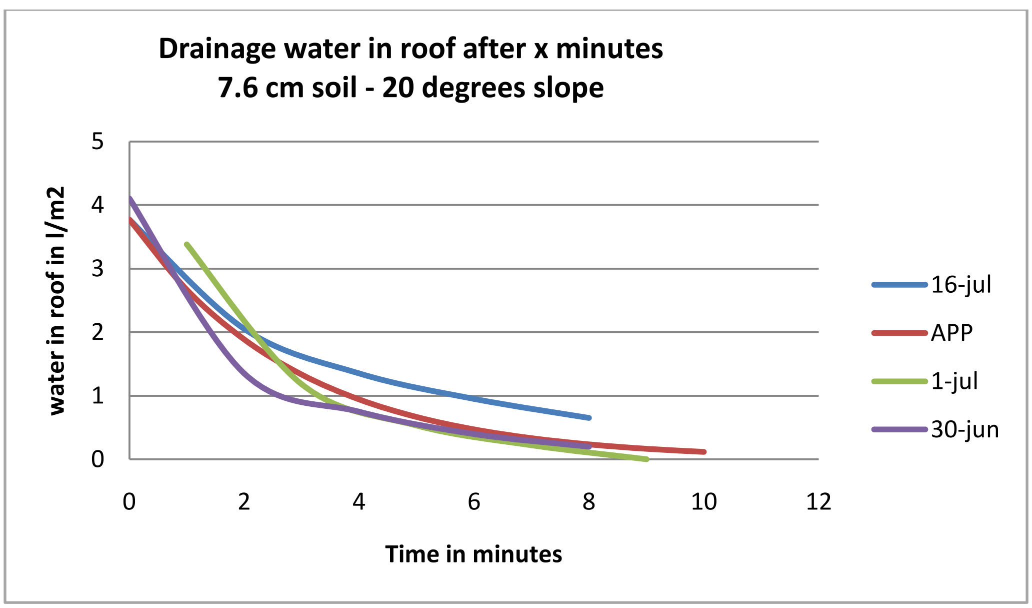


Figure 28 Drain water in roofs after x-minutes 7.6 cm soil - 20 degree slope

As shown in the graphs the twenty degree sloped roofs have lower capacity to drain. This is because direct runoff from the roof appears. Also less time is needed for the water to leave the roof.

Influencing parameters Drainage

Soil buildup

The porosity is a direct influencing factor in the drainage of water. (eq. 7) A lower porosity can decrease the speed of water running out, but this effect will probably not be that big, because of little drain paths in the green roof or the presence of a drain layer, which already make sure that green roofs can release the rain water quite quick.

Slope

For green roofs with larger slopes the drainage capacity in theory is bigger, but due to direct runoff this is not used for delaying water. Only about 40% of the drainage capacity is used. With a high slope water leaves the roof at a higher speed in comparison with a non sloped green roof and has thereby worse runoff delaying capabilities than the non sloped roofs. The difference in half value time of the total amount of water which has to be drained between the 2 degree roof and the 20 degree roof has about a factor three.

Higher slopes increase the possibility of erosion of the top soil layer during heavy rain events. No actual research has been done on this topic, but more than 20 degree slope is not considered to be wise full.

Drainage layer

A drainage layer could be added to enhance the discharge of rainwater. This will lower the effect of the time delay. No actual research has been done on this subject.

Intensity rain event

The intensity of a rain event has an influence on the drainage capacities of green roofs. The drainage of green roofs works better in high intensity rain events than in low intensity rain events.

Roof size

The test results were retrieved from relative small green roofs with a short drain length. A longer drain length (roof) will approximately have the same curve because the drain length in the equation of Darwin will increase with the same factor as the total head.

However for very large green roofs the resistant factor (first part of the Darwin equation) $A \cdot \frac{k}{n}$ will probably increase due to the fact that individual drain paths have less influence on a greater surface. This means that bigger green roofs probably have better capabilities for a longer time delay. More specific research could deliver better results.

Drainage conclusion

The capacity of green roofs to delay discharge of precipitation is bounded by its (effective) drainage capacity and the intensity of the precipitation.

Boundaries tell that a 2 degree green roof has a capacity to delay about 6 – 7 liters per square meter (or mm precipitation). The measured half value time for the 2 degree green roofs is 6 minutes. This means that after 6 minutes 50% of the drainage water has left the green roof. After another 6 minutes another 50% from the remaining drain water has left. This means that after 12 minutes 75% has left. And so on.

For 20 degree green roofs the total capacity in theory is higher, but due to direct runoff the amount of drain water which can be delayed is lower. Measured amount are between 3 – 4 liters per square meter (or mm precipitation). The measured half value time for the 20 degree green roofs is about 2 minutes. After 2 minutes 50% of the total amount of drain water is drained. After 4 minutes this is 75%.

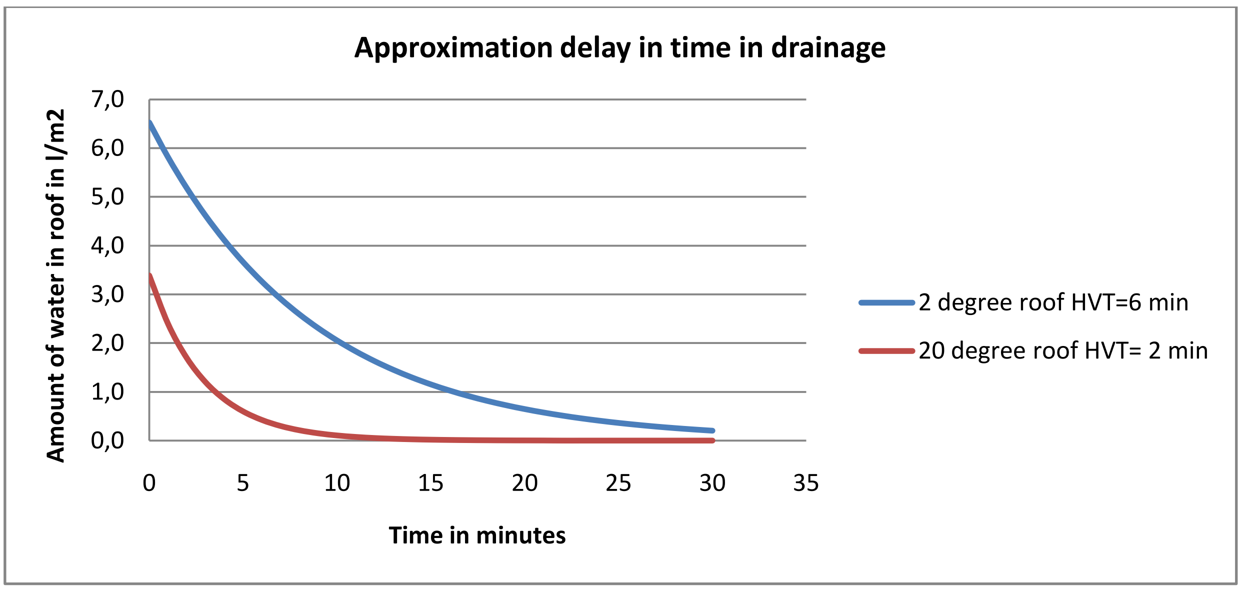


Figure 29 Approximation in delay in time in drainage

Larger roof sizes could make that it take a bit more time for green roofs to lose the water. However the boundaries will not change. So the maximum area of influence stays about 6-7 mm for non sloped roofs and 3-4 mm for sloped roofs.

The thickness of the substrate layer has not a direct influence on the Half Value Time (measured 5.1 and 7.6 cm). But only on the amount of water which will be delayed conform the change in drain capacity with different thicknesses of roofs.

3.6 Conclusion water handling capacities

For extensive green roofs with soil layers up to 7.6 cm of soil the boundary conditions have an upper limit of about 32 liters water per square meter. This maximum decreases with lower soil thickness and lower porosities. The maximum water content is divided into three areas: the drain capacity, the retention capacity and the bottom capacity. The results for the investigated four test green roofs are given in the graph below:

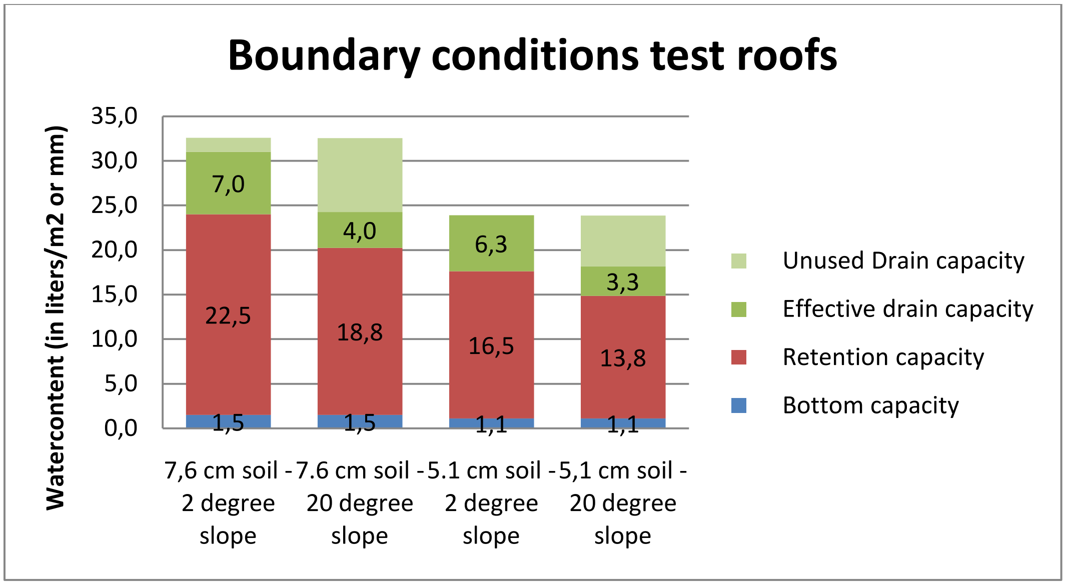


Figure 30 Boundary conditions test setup results

Only a relative small part of the retention capacity is actually used for retention. This due to the fact that evaporation rates and an aggressive irrigation strategy limit the time for green roofs to evaporate water to free space for the retention of a future rain event. The evaporation rate of 5 mm per day and a irrigation strategy with irrigation after one day without precipitation maximize the retention capability of green roofs on about 5 liters per square meter or 5 mm of precipitation.

Drainage results show that green roofs can delay a certain amount of water. For flat roofs this is an effective capacity of about 7 mm of precipitation with a half time value of 6 minutes. If the green roofs are placed under a roof of 20 degree the effective drain capacity decreases to 3-4 mm of precipitation with an half time value of 2 minutes. Other not examined configurations of green roofs leave space for different times of delay, but will be more or less in the same order of amounts.

4. Research: Implementation

To answer the question if green roofs can improve the water management system in an urban, tropical and undeveloped area an estimation of the influence of green roofs on the city of San Pedro Sula is made.

This is done in the following order:

1. Characteristics of San Pedro Sula
2. Precipitation data of San Pedro Sula
3. Theoretical influence of green roofs
4. Large scale green roof engineering

4.1 Characteristics of San Pedro Sula

The city of San Pedro Sula is a large city situated in the Sula Valley. On the west side of the city a large mountain, the Merendon mountain range, makes a natural border. The mountain generates a slope in the city. This slope is about 2.5%. (No actual source, in agreement with supervisor) The more wealthy habitants have their houses in the higher part (Westside) of San Pedro Sula. The less wealthy inhabitants live in the east part of San Pedro Sula. It is said that the main street from north to south separates the two classes, but this is a very rough estimation.

Due to the natural slope the lower east part of San Pedro Sula collects a lot of rainwater. The economical damage which occurs due to the flooding of the streets hits the less wealthy people of San Pedro Sula the most.

Figure 31 City map: San Pedro Sula

Source: (Google earth, 2009)

Rough estimation surface characteristics center:
Roofs: 40%
Roads: 30%
Other: 30%
(Google earth, 2009)

Percentage zinc roofs:	80% in urban areas in whole Cortes
Percentage other roofs	20% in urban areas in whole Cortes

(estadistica, 2001)

Rivers in San Pedro Sula

The rivers which have their spring in the Merendon mountain range are the main canals to drain precipitation. Eventually the rivers end up in the Atlantic ocean on the north.

Source: (Meeroff, et al., 2004)

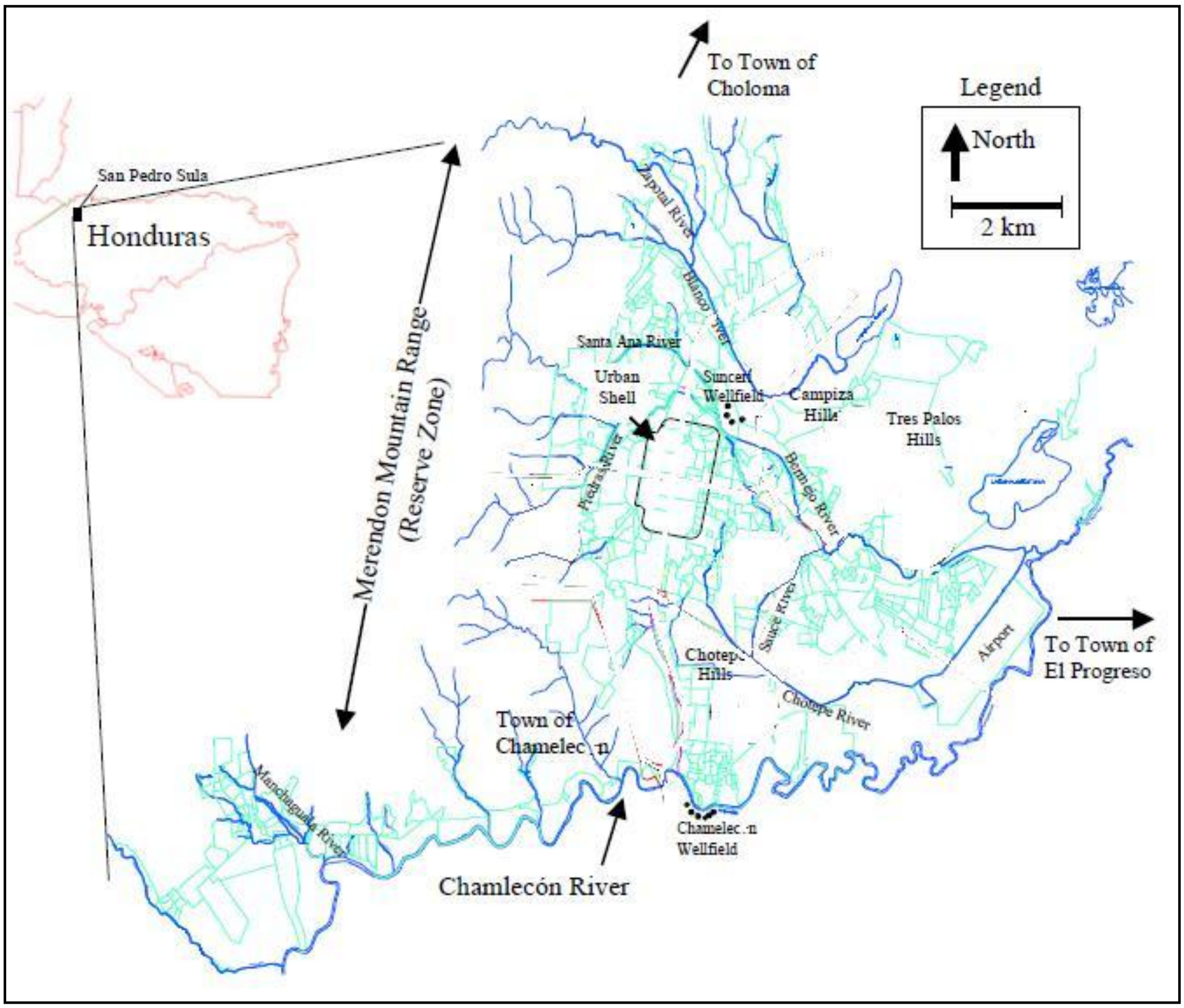


Figure 32 Map San Pedro Sula with rivers

Sewer system

Precipitation which falls in San Pedro Sula is collected by the roofs and streets and is supposed to be drained by the sewer system to the rivers. However the sewer system does not cover the entire city of San Pedro Sula and a big part of the sewer system is poorly maintained. A few pictures taken in the city center of San Pedro Sula illustrate this image. A lot of garbage is dumped into the rainwater collectors and other collectors are completely filled with sand.

Figure 33 Pictures sewer system San Pedro Sula

As a result of this poorly maintained sewer system the discharge of rainwater to the rivers is taken over by the streets. During rain events the streets are fully covered with water. The pictures underneath were taken with precipitation rates of only 20 mm and in an area where the sewer system looks quite well.

Figure 34 Pictures Water on streets after rain event

4.2 Precipitation analyses of San Pedro Sula

A ten year dataset of daily precipitation data was retrieved from the División Municipal de Agua (DIMA, 1997-2006) in San Pedro Sula. Employees from DIMA measured precipitation rates on a daily basis during several years on different locations around San Pedro Sula. Due to cost reductions the measurement of several stations were stopped after the year 2000. After 2006 the measurements of the daily precipitation has stopped completely. Nowadays a weather station located near the airport of San Pedro Sula retrieves daily precipitation data, but these data are send automatically to Tegucigalpa and were not accessible for the researcher in a cost effective way. The used data set was obtained from 1997 to 2006 on the station El Ocotillo, located 5 km east of the city center.

Representativity El Ocotillo

The precipitation amounts measured at the station of El ocotillo are quite representative, because the station is not too far located from the city center itself. Because of the necessity of having a wide range of data on a daily basis these data are used for calculations on the impact of implementation of green roofs in the city area. However also two years of precipitation data from a station located near the mountains (Villas Mackay) have been examined. This has been done to see if the daily precipitation data set of El ocotillo is governing for the whole region of San Pedro Sula. The two years from Villas Mackay show 15% to 48% higher amounts of precipitation on a yearly basis. It should be considered that higher amounts of precipitation take place closer to the mountain range and thereby the city center as well.

Nevertheless the data from El ocotillo show a good insight of the yearly amounts of precipitation and the distribution of this precipitation throughout the year.

Figure 35 Map location precipitation measurements

(Source: Google earth, 2009)

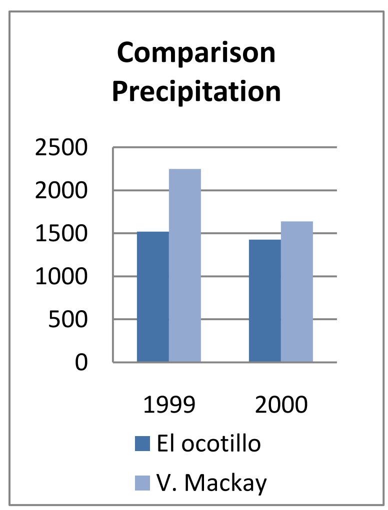


Figure 36 Comparison precipitation El ocotillo - Villas Mackay

Yearly precipitation

Yearly precipitation data in San Pedro Sula derived from the dataset.

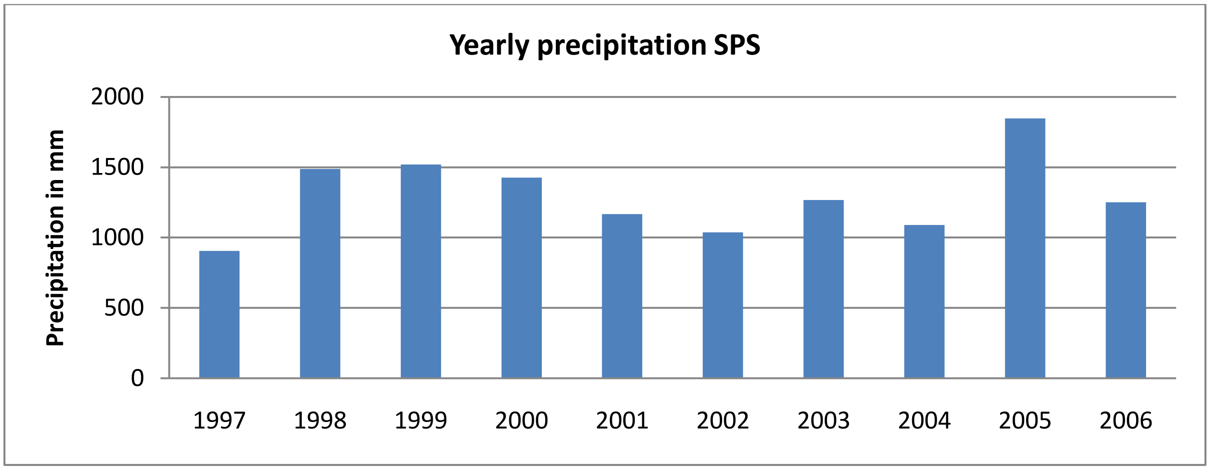


Figure 37 Yearly precipitation San Pedro Sula

The graph shows a pretty irregular appearance of precipitation rates in San Pedro Sula. Statistical no rising line in precipitation values could be derived. The high amount of precipitation in 2005 is highly influenced by the tropical storm Gamma. In 1998 hurricane Mitch is responsible for a respectable amount of precipitation. Tropical Iris appeared in 2001.

	min	average	max
Precipitation in mm:	905	1301	1842

The average precipitation rate is 1301 mm in a year. This amount of precipitation is divided throughout the year as presented in the following graph.

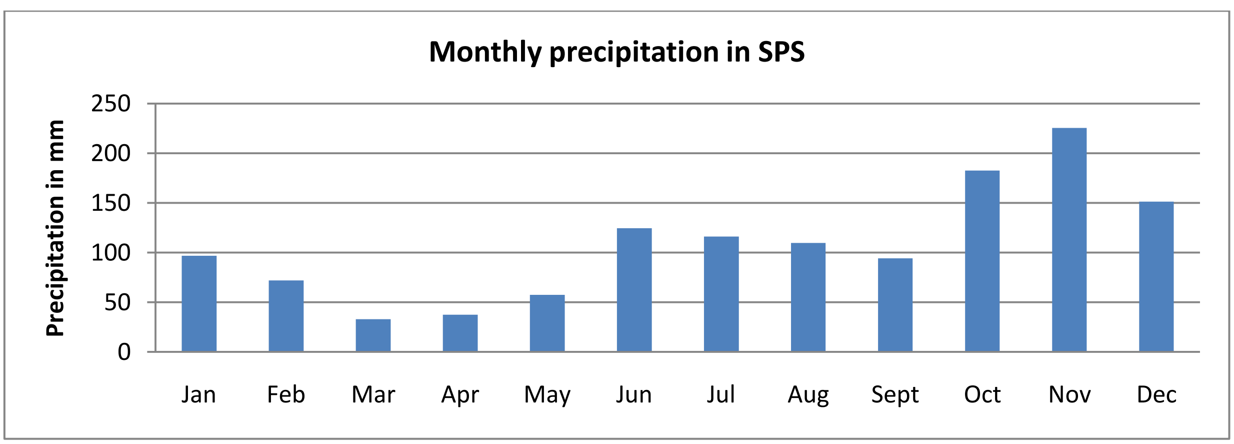


Figure 38 Monthly precipitation San Pedro Sula

The period of February to May show lower amounts of precipitation. From October to December a higher amount of precipitation is measured. As well Mitch, Gamma and Iris appeared in this period.

Distribution of rain events into categories

It is interesting to look more specific on the distribution of rain events in different categories of amount of precipitation. The numbers derived from the dataset will give an idea of the possibilities of green roofs to handle the amount of precipitation in different rain events.

	Average amount of days per year
Days with precipitation	117
Days without precipitation	248

The 117 days with precipitation are divided into three different categories. This will provide an insight of the occurrence of small, medium or heavy rain events throughout the year. The categories are chosen to make clear the difference in amount of days and the average amounts of precipitation in these categories. A picture is added in paragraph 4.1, picture 34 to have an idea of an 20 mm rain event. The picture shows that already heavy water flows on the streets start to appear. The influence of the middle and heavy rain events have an even bigger influence with, in heavy cases, severe flooding as a result.

	Average amount of rain days per year	%	Average amount of precipitation in mm	%
Annual total	117	100%	1301	100%
0-20 mm	99	85%	575	44%
20-40 mm	12	10%	305	24%
>40 mm	6	5%	419	32%

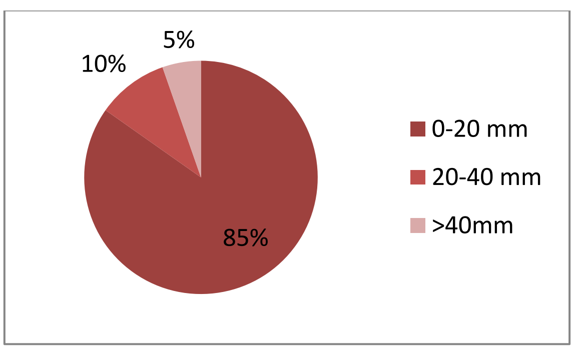


Figure 39 % days with precipitation in different categories

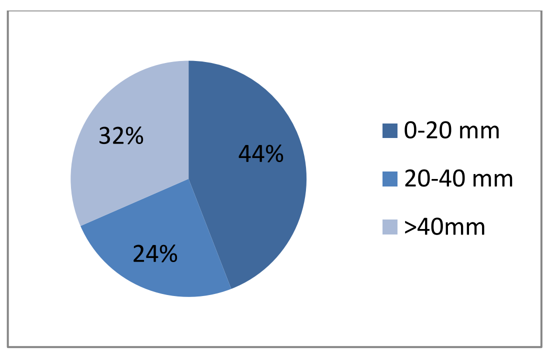


Figure 40 % amount of precipitation in different categories

As shown in the tables and figures the 85 % of precipitation days with relatively small amounts of rain water are responsible only for 44% of the total annual precipitation. The 5% of days with heavy rain events are still responsible for 32% of the annual precipitation.

To complete the image of the distribution of rain events and precipitation amounts throughout the year also the average monthly results are presented in graphs.

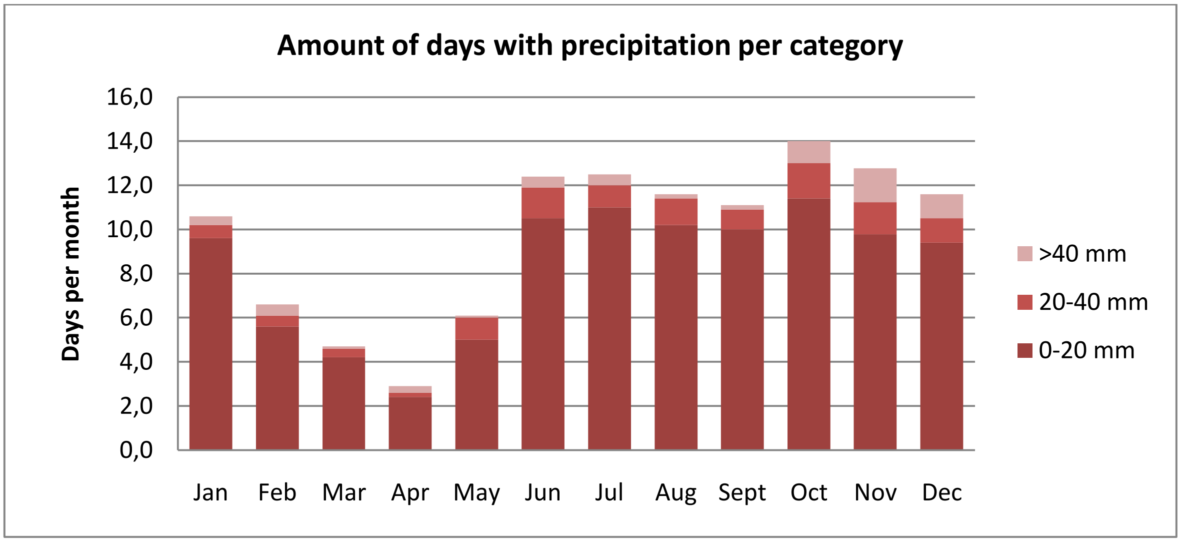


Figure 41 Amounts of days with precipitation per category

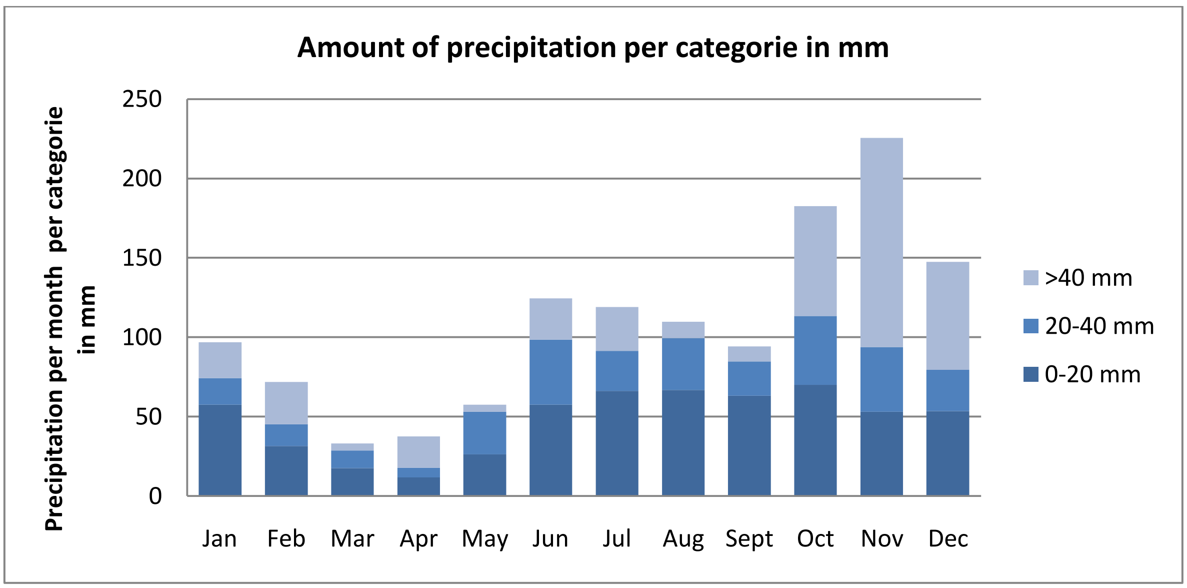


Figure 42 Amount of precipitation per category

As shown on the yearly precipitation days and amounts the large amount of days with small amounts of precipitation only take a relative small part of the total monthly amount of precipitation. Only the few days in a month with high amounts of precipitation take a relative big part of the total monthly precipitation. The graphs from the months October, November and December speak for themselves.

Appearance heavy rain events

The precipitation category which affect the society the most are the precipitations in the heavy precipitation category. A detailed oversight of these heavy rain events is presented in the next table.

	Precipitation days	Precipitation days
	1997-2006	Year average
40-50 mm	22	2,2
50-60 mm	15	1,5
60-70 mm	9	0,9
70-80 mm	4	0,4
80-90 mm	3	0,3
90-100 mm	1	0,1
>100 mm	7	0,7

Figure 43 Appearance heavy rain events

4.3 Theoretical influence of green roofs

Combining the data of the water handling capacities of green roofs with the yearly precipitation amounts in San Pedro Sula delivers an insight of the capacity of green roofs to deliver a positive effect to the water management system. The results are summarized for the different categories of rain events.

At the horizontal axe of the graphs stands a possible amount of precipitation. That same amount is handled by a green roof, but divided in different ways. A part of the precipitation is retained. A part of the precipitation is delayed for more then 2-6 minutes (depending on the roof slope). A Part is delayed for less than 2-6 minutes. And the rest of the precipitation is run off like on a normal roof.

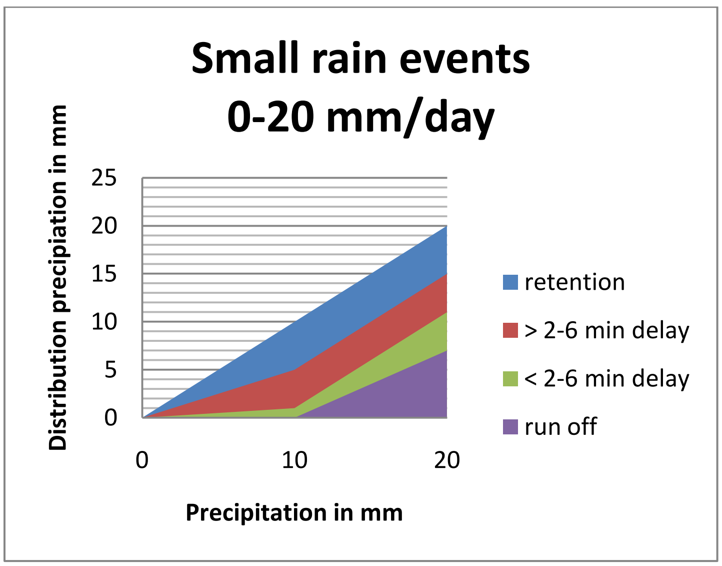


Figure 44 Influence green roofs on small rain events

The influence of green roofs on the small rain events, which occur 85% of the precipitation days, is quite substantial. The green roofs are able to take up a part of about 5 mm and also are able to delay a certain amount of water between 0-4 mm for about 2 to 6 minutes depending on the intensity of the rain event and the slope of the roof. However these rain events do not cause a lot of bad effect. The negative aspect of rain events start to arise in the categories with middle and heavy rain events.

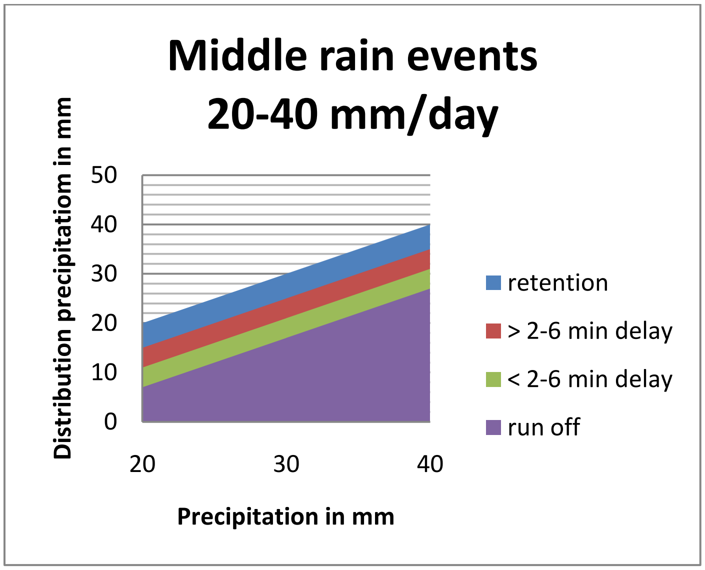


Figure 45 Influence green roofs on middle rain events

The influence of green roofs on the category of middle rain events, which occur 10 % of the rain events, is relative a lot smaller than on small rain events. About 5 mm can be retained and also a certain amount of water between 0-4 mm can be delayed for about 2 to 6 minutes depending of the slope. However the total influence on these rain events is way less due to the fact that green roofs just cannot handle more precipitation. A large part of the precipitation is just normally discharged to the sewer system.

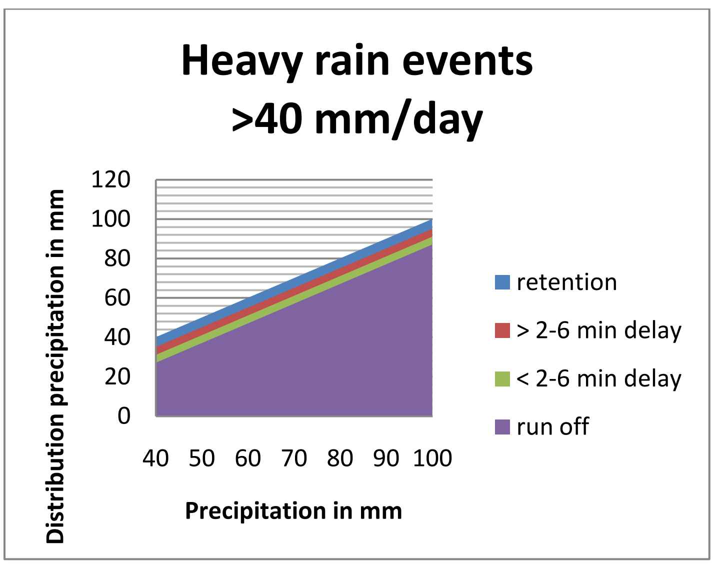


Figure 46 Influence green roofs on heavy rain events

The influence on the heavy rain events, which occur 5% of the rain events is at last very small. Still about 5 mm can be retained and also a certain amount of water between 0-4 mm can be delayed for about 2 to 6 minutes depending of the slope. However the total influence of having a green roof is relative small. As shown in the graph a large part of the precipitation just acts as run-off, like on a normal roof. The influence area is for the 40 mm rain events about 25% and for the rain events over 100 mm the influence area is only about 5 to 10%.

Other research:

A comparison with other research on green roofs proved to have some difficulties. Some of the investigations present results in percentages of run off or in a curve number (Appendix B). These results were not presented for different categories of rainfall and thereby it is not possible to draw a good conclusion on the rainwater handling capacities of green roofs for heavy rain events. The research conclusions of the other investigations are presented to have a general idea of the retention abilities.

(Van Woerd, 2005) did a study in the US on three different types of roofs: A commercial roof with gravel, with an extensive roof without vegetation and an extensive green roof with vegetation (4cm substrate). Results range from 48.7 percent retention for gravel to 82.8% for an extensive green roof with vegetation. Again this is not analyzed with a distinction in different rain events. So these results do not tell a lot on the possibilities of green roofs to improve the rainwater management system in severe circumstances.

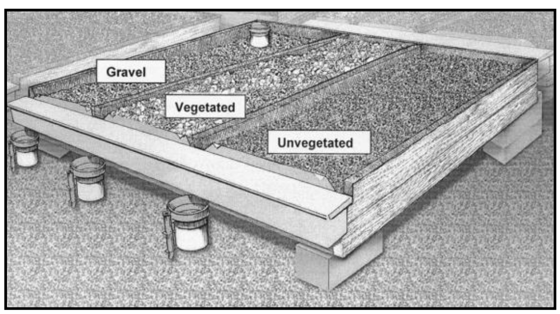


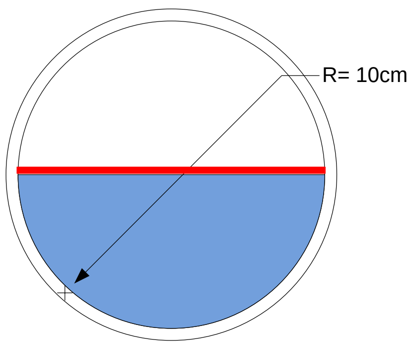
Figure 47 Test setup (van Woerd, 2005)

Another research founded in the US report 100% retention in summer conditions on 8-10 cm roofs, but much lower retention (20%) in winter conditions. The total amount of water taken up on an annual base is estimated on about 50% (Berghage R.D, 2009)

4.4 Large scale green roof engineering

To establish a general idea of the influence of green roofs on a larger scale a comparison is made with a normal house:

> A normal house with a roof of 100 m^2 will retain a maximum of about 5 liters of precipitation per square meter. In total this is 500 liters; the size of two big rain barrels. Imagine the difference it would make on the streets.
>
> Another calculation can make visual what the influence of having a green roof with a small retention of rain water has on a pipe line from a house to the sewer system.



Assumptions:

- Same house 100 m^2
- Retention 500 l (less run off)
- Time period rain event: 20 min
- Diameter pipe line: 10 cm
- Velocity of water in pipe 1m/s
- Fluctuating water level in pipe

> 500 liters per twenty minutes is the same as 0.414 liters per second. With a velocity of 1 m/s this delivers a section of 0.0414 dm^2. If the pipe is already halfway filled with water the difference in discharge would only be the thickness of the redline. A difference in height of 0.41 cm on a scale of 10 cm

These examples show that the influence of green roofs on the water management system are relatively small.

It should also be considered that as described in the characteristics of San Pedro Sula not the whole city consist of roofs. A large percentage of the precipitation will pass the roofs and go directly to the streets or other surfaces. Possible installed green roofs don't influence that flow of precipitation.

Applying the green roof concept on big industrial buildings will be the most profitable to have an effect, due to the fact that rainwater is retained on a concentrated place. However as shown in the theoretical influence of green roofs the influence of these green roofs is very limited.

Figure 48 Large scale green roof

Benefits house owner

Benefits for the house owner concerning green roofs do not appear because of the water handling capacities of green roofs. The effect, certainly in heavy rain events is too small. The capability of green roofs to lower the temperature inside a structure is a promising benefit for the house owner itself. (Meijer, 2009) Besides that it could be nice to live in a green environment.

Benefits municipality

The benefits of green roofs in a city on a very small scale have an really small effect on the water management system of a city. The capacity to handle rainwater is just too small. However concerning the water management in a city the municipality should encourage people to think about a green roof for their own benefits, because the water handling capacities of green roofs will always have a (small) positive effect.

5. Conclusions

The main research question was if green roofs are a good design solution to improve the water management system in an urban, tropical and undeveloped environment. To answer this question the water management capacities of an inexpensive extensive green roof design have been examined in the tropical city of San Pedro Sula. Due to the fact of a short research period the investigation has been approached from a water balance point of view.

The boundary conditions tell us the total amount of water which can be handled by a green roof. For example the water handling capacity is about 32 mm of water for an extensive green roof with a 7.6 cm thick soil layer and the local used soil mix. This 32 mm of water is divided into three areas: The bottom capacity, the retention capacity and the drainage capacity. Out of these boundary conditions two main issues have been extracted.

3. The evaporation rate per day. This is the amount of water which leaves a green roof and therefore equals the retention capability when a new rain event approaches. The retention capability is limited by the fact that an aggressive irrigation strategy is used which waters the green roofs after one day without precipitation. The maximum amount of water which can be retained is therefore maximized by the evaporation rate of one day. This is about 5 mm of water. If a better plant type can be found which survives with a less frequent irrigation strategy the retention capacity can be a bit higher.
4. The second issue is the ability of green roofs to delay the discharge of water. This gives the sewer system more time to handle large amounts of precipitation. The boundary conditions maximize this drain capacity at 3.5 to 8 mm, depending on the size and slope of the roof. Half of this amount is delayed more than between 2 and 6 minutes depending on the slope of the roof. Other not examined configurations of green roofs leave space for different times of delay.

These rainwater management capacities have been compared to the precipitation data of ten years in San Pedro Sula. These data were organized in small, middle and heavy rain categories.

Small	0-20 mm/day	99 days per year
Middle	20-40 mm/day	12 days per year
Heavy	40 -200 mm/day	6 days per year

The influence of green roofs with their maximum of 5 mm retention and the ability to slow down 2 to 4 mm for 2 to 6 minutes is a positive number, but certainly on the heavy rain events the influence is limited. It should not be considered that green roofs can totally solve problems with the discharge of precipitation. A well maintained sewer system stays a governing design solution.

5.1 Recommendations

- A more adaptive irrigation strategy could improve the retention capabilities of green roofs, but the main reason for irrigation should be to keep the plants alive. Also with a more adaptive strategy the influence of green roofs on heavy rain events stays limited.

- Because of the relative small positive effect of green roofs on the rainwater management system, this effect should be considered as a positive side effect, but not the main reason to install green roofs. Esthetic reasons and temperature benefits should be governing.

- The negative effects of heavy precipitation in San Pedro Sula should not only be fought with the introduction of green roofs and reduction of permeable areas. The precipitation rates are that high that a well maintained sewer system should be the governing measure to suppress the negative effects of heavy rain events. A lot can be done with adequate maintenance and a well designed discharge plan. This is a good subject for more research.

- The benefits for the municipality of installing green roofs are not that high. Only with a large cover area the green roofs can really have an influence. It should be considered that investment costs should be paid by the house owner because the benefits of the green roofs are mainly for the house owners (cost reduction because of decreasing inside temperatures). A cost analyses was made by (Meijer, 2009)

- It should be considered that discharge water of green roofs has more nutrients in the water because it has passed a soil layer. Several researches have been done on this subject. A close look on this subject can tell if there are possible negative results if green roofs are implemented on a large scale.

- Another way to reduces discharge of rainwater is to convince people to collect rainwater in a rain barrel. This water can be used for several other purposes. This has been practiced in The Netherlands too.

- The run off decreasing pavement mentioned in chapter 3.4 is a way to improve water handling capacities. It should be considered that they need more maintenance than original pavements.

Appendix A – Visualization build up test setup

The test setup used to measure the retention and drainage capacities of green roofs was built in de first two weeks of the research.

Figure 49 Green roof layer one: Metal sheet

Figure 50 Green roof layer two: Plastic layer

Figure 52 Green roof layer three: Geo-textile

Figure 51 Green roof layer four: Soil 5.1 & 7.6 cm

Figure 54 Green roof layer five: Addition of grass

Figure 53 Green roof - rainwater measurement system

Appendix B – Runoff prediction technique: Curve Number Method

Another model used by researchers to describe the total amount of runoff of a green roof is an existing theory for estimating runoff for large area's to make dimensions of sewer systems.

The Curve Number Method (ASCE, 1996)

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

with

$$S = \frac{1000}{CN} - 10 \qquad \text{(Eq. 16)}$$

Where:

Q average flow rate
P precipitation
I_s Initial itraction (0.2 S)
S Runoff parameter
CN Curvenumber

With a known curvenumber of a surface and the graph below it is possible to make a prediction of the amount of runoff from a certain area.

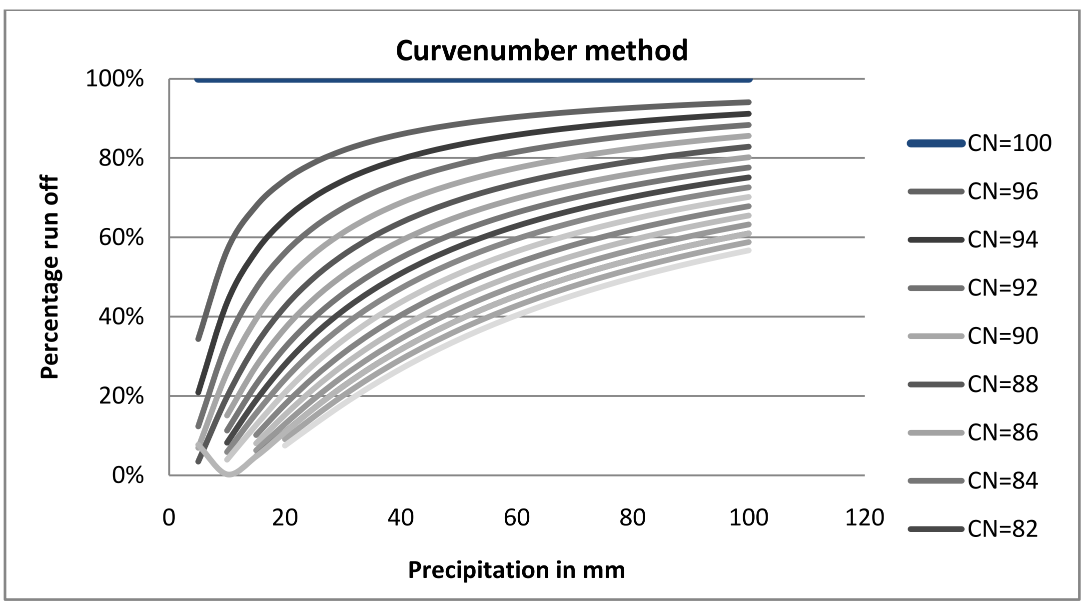


Figure 55 Example curve number method

Curvenumbers range from 0 to 100. A curve number of 100 has a runoff of 100 percent. For impermeable surfaces normally a CN factor of 98 is used. (ASCE, 1996). For Agricultural lands the CN is about 70-90.

Typical curve numbers

Description of Land Use	Hydrologic Soil Group			
	A	B	C	D
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Woods and Forests:				
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84
Source: (Chow, 1988)				

Figure 56 Typical curve numbers

The advantage of the presentation of estimated runoff with the curve number method is that it can easily be used by engineers who design water drainage systems in a city. This method is frequently used. (ASCE, 1996) (Getter, et al., 2007)

A comparison between the empirical curve number method and the research results based on a balance approach (chapter 2.5) should give an idea of the curvenumber which should be used.

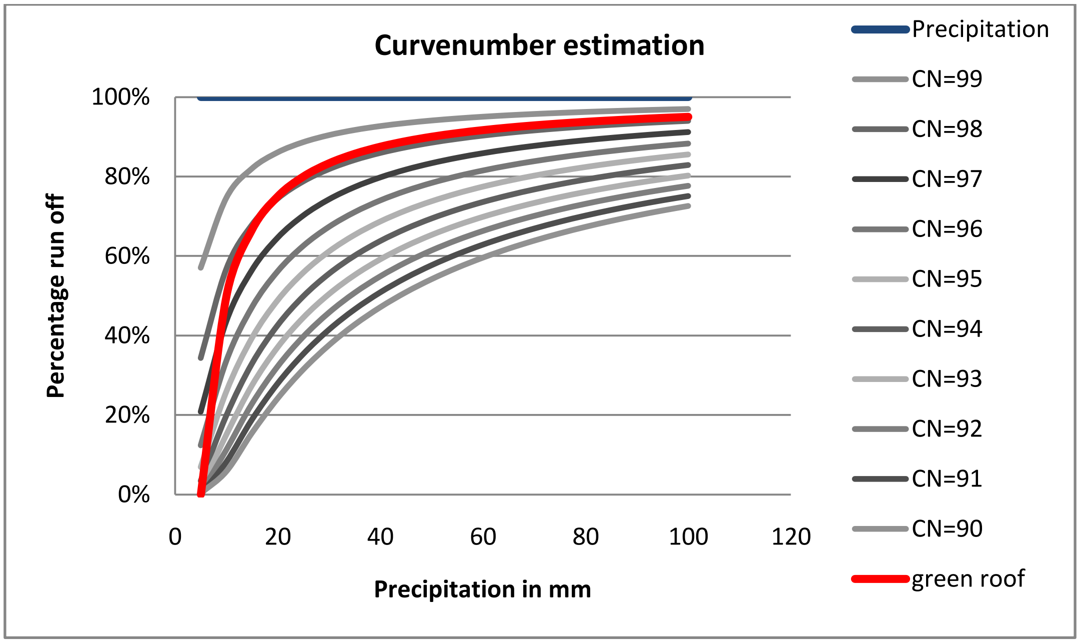


Figure 58 Green roof curve number

The matching curvenumber is 98. Also the average curvenumber which is measured during seven rain events is 97.4. (Data report)

The reason for this curve number to be this high is the Antecedent Moisture Content (AMC). For average circumstances the average CN used is with an average Antecedent Moisture Content (AMCII). Due to the fact that the green roofs receive daily irrigation the curvenumber should be replaced by a High Antecedent Moisture Content (AMCIII) and therefore the curvenumber is this high. An average curvenumber without irrigation for the tested green roofs would be 94.

CN AMC II	CN AMC I	CN AMC III
100	100	100
98	94	99
96	89	99
94	85	98
92	81	97
90	78	96
88	75	95
86	72	94
84	68	93
82	66	92
80	63	91
78	60	90
76	58	89
74	55	88
72	53	86
70	51	85
68	48	84
66	46	82
64	44	81
62	42	79
60	40	78

Figure 57 Table AMC- CN

Other research: curve number method

Getter et al. did a research at the Michigan State University. Presented runoff curve numbers range from 84 to 90 for different roof slopes. (Getter, et al., 2007) These lower curvenumbers are reasonable because of the fact that no daily irrigation is applied.

Additional runoff reducing surfaces

In considering of the curve number method another type of city designing is applied in the Plaza Comercial Bioclimática. Pavements for pedestrians can be made out of concrete blocks with space for vegetation. These areas are more permeable and rainwater is able to directly drain to the soil instead of being drained to the sewer system. This has a positive effect on the discharge of rainwater to the sewer system, although this system also has its limitations. Maintenance has to be done on the grass to make sure that the city looks presentable.

Figure 59 Pictures permeable pavements

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