BACHELOR THESIS

"Reproducing runoff initiation in an environment that has dynamic initial abstractions"

Aiuaba Experimental Basin, Ceará, Brazil.

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Submitted to the Hidrosed research group of the Federal University of Ceará, Fortaleza, Brazil

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Preface

In front of you is the bachelor thesis "Reproducing runoff initiation in an environment that has dynamic initial abstractions", performed at the Federal University of Ceará (UFC), Fortaleza, Brazil. This bachelor thesis is the last step towards accomplishing a bachelor degree in Civil Engineering at the University of Twente (UT), Enschede, The Netherlands.

In collaboration with the Hidrosed Research Group this research was conducted from the 29th of August till the 13th of November in the year 2015. During this period prof. J.C. de Araújo (UFC, Hidrosed) and Dr. M.S. Krol (UT) have accompanied me. Hereby I want to thank them for helping me during the process of completing this bachelor thesis. This thesis would not have been possible without their time and support. Above all I want to thank all the other students from UFC that have made stay in Fortaleza unforgettable.

Hidrosed, *Grupo de Pesquisa Hidrosedimentológica do Semiárido* (loosely translated into Research Group of Sediment in the Semi-Arid Region), is a research group that belongs to the Department of Agricultural Engineering of the Federal University of Ceará. The group measures and is modelling sedimentary processes of the semiarid region in the northeast of Brazil. Hidrosed their main goal is to conduct research concerning the availability of water and to identify the influence of erosion and sediment yield in surface water supply reservoirs.

Hidrosed utilises the Aiuaba Experimental Basin (AEB; 11.5 km^2) to perform research. In the AEB, a weather station and other measuring instruments are installed. Data like rainfall, soil moisture and outcomes of Parshall flumes are collected. In this research data from the AEB will be used.

As long as the world population is increasing, the amount of available fresh water per capita decreases. Although the growth of the Brazilian population is stagnating, the overall population still increases (The World Bank, 2015). Another phenomenon that is closely linked to population growth is climate change, this is causing an extra pressure on the availability of fresh water (UNESCO, 2012). Especially for the semiarid region of Brazil it is valuable to perform research about water availability.

The first chapter of this thesis introduces the subject. The chapter gives information about the AEB. Furthermore the objective of this research and the related research questions will be discussed. In the second chapter the research design will be discussed. Firstly the background of the used terminology will be given. Secondly, the definition of the applied models will be elaborated. In the remaining sections of the second chapter the methodology, review functions, the method of generating time series and the method of running the models will be clarified. In chapter three the final results are shown. In this chapter the review functions are used to interpret the results. The fourth chapter contains the conclusions and the fifth chapter contains the discussion and recommendations.

Summary

In this research the Wasa and Dicasm models are validated concerning runoff initiation in the Caatinga biome. Runoff initiation for the model outcomes is calculated as runoff above zero millimetres per event. The Aiuaba Experimental Basin (11.5 km^2) is the study site of this research.

Research has shown that runoff initiation in the basin is dynamic and seasonal. Runoff initiation is considered as dynamic because tree roots shrink during dry periods. After that, precipitation will fill the pores that arise after that dry period whereby less or no runoff will occur. When the pores are saturated, precipitation will run off in almost all cases. Next to that the root depth in the Caatinga biome is about 15% smaller in dry season compared with the rainy season.

The aim for this research is to identify a way to simulate runoff initiation in the AEB. Since field measurements show the aforementioned dynamic behaviour, the models should be able to simulate that similar behaviour. Several hydrological models will be run for 116 runoff events in the period from 2005 until 2014. All these events will be run after initial conditions of the models. The main objective of this research is described as: "to assess the specific validity of Wasa and Dicasm for application, by analysing their ability to explain runoff initiation at the event scale in the Caatinga biome".

The results of this research show that both models give show a smooth relationship between precipitation and runoff depths or cumulative initiation. Measurements conducted in the AEB show higher deviations. Furthermore both models are overestimating runoff initiation. Wasa produces for every event within the AEB runoff in case of precipitation higher than 15 mm. Dicasm produces runoff even for events with low rainfall magnitudes.

In Dicasm the base percentage is used instead of the infiltration and water store mechanisms. This formula is not suitable to show any dynamics and cannot distinguish runoff initiation since there will be always runoff for each precipitation. This might be caused by the short run time of just one day, whereby the more extensive systems that are used by Dicasm are not considered.

The contingency table in the results shows that for all events Wasa agrees in 37% of the cases. For events up to 31 mm 38 out of 78 (roughly 50%) of the runoff initiation is predicted correctly.

It can be concluded that the used models do not consider the aforesaid dynamic behaviour. In general, the higher the precipitation, the more intense runoff. Therefore no similar rainfall events result in different runoff and vice versa.

Contents

1 Introduction

Water is one of the most valuable natural resources of the world. Most economic aspects are linked to the availability of water. It is the key element for environmental conservation and economic development and water is therefore fundamental for a sustainable life (WHYCOS, sd). The outcomes of hydrological models are a necessary building block for policy elaboration, plan establishing and for carrying out projects. However, those models describe a simplified reality (Stowa, 2010).

This research is about tackling issues that have to do with adapting an important hydro-environmental mechanism, the root system, into hydrological models. Therefore the WASA-SED model (hereinafter Wasa) and Dicasm will be validated with respect to that parameter, concerning runoff initiation in the Caatinga biome.

In this chapter the background of this research will be given. It starts with a paragraph about the importance of hydrological modelling and after that the objective and research questions will be presented.

The terms of reference, formulated by professor de Araújo, can be found in Appendix A . The terms of reference are the initial intentions of this bachelor thesis, however they have changed during the process of finishing this thesis.

1.1 *The Aiuaba Experimental Basin*

The Aiuaba Experimental Basin (hereinafter AEB) is the study site of this research. It is located in the semiarid Caatinga biome. It covers an area of about 11.5 km^2 and is located near the city of Aiuaba in the state of Ceará, Brazil. The basin is shown in Figure 1-1.

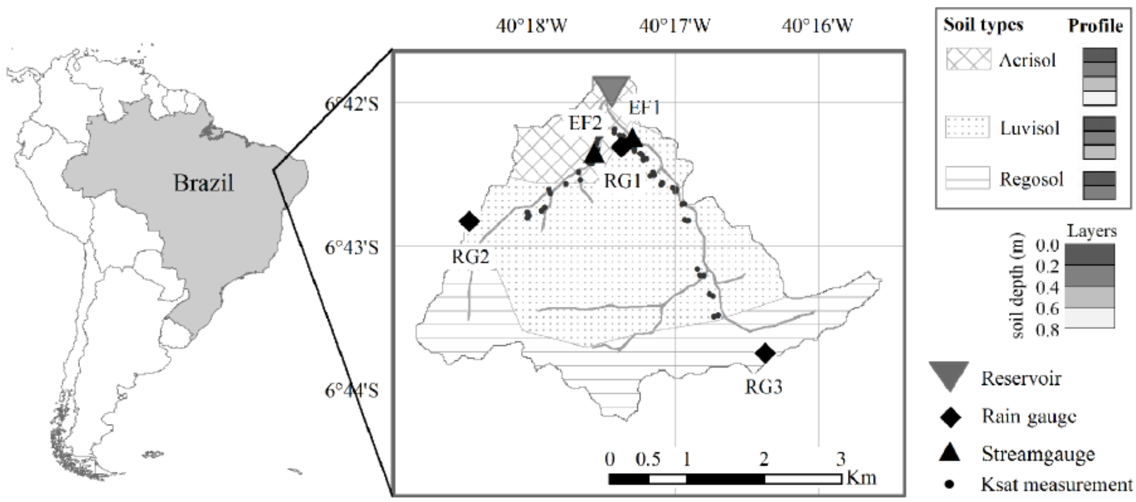


Figure 1-1 Location and geography of the AEB. In the basin 3 rain gauges are installed, however only data of 1 rain gauge was available during the research period and therefore used. Reprinted from "Runoff initiation in a preserved semi-arid Caatinga small watershed" by de Figueiredo et al, 2015.

The basin consists mainly of three soils: acrisol (southern hill), luvisol (center) and regosol (reservoir). According to de Figueiredo et al. (2015) the southern parts of the basin are crystalline, the more northern parts are metasedimentary.

As mentioned before the basin is situated in a semiarid area (a steppe climate Bs according to the classification of Köppen). The average precipitation is 560 mm per year and it has a potential evapotranspiration of 2600 mm per year (de Figueiredo et al. 2015).

1.2 Objective

De Figueiredo et al. (2015) have tried to identity the best explanation for runoff initiation, based on hydrological variables. They have calculated runoff according to a water balance and they define runoff initiation as runoff higher than 0.1 mm per day. That threshold value is applied because of the used estimation process, which includes several uncertainties. To distinguish runoff initiation or not, this threshold value is also applied to the results of de Figueiredo et al. For the model outcomes no threshold is used.

To show the dynamics of the basin, the researchers stretched an example. The first event (with daily precipitation of 26 mm and a maximum 60-minutes intensity [hereinafter I_{60}] of 22 mm h^{-1}) did not generate runoff, but another event (with precipitation of 16 mm and an I_{60} of 16 mm h^{-1}) actually did. Both rainfall events had an antecedent soil moisture of 0.33. The researchers suppose this contrast is caused by the root system of the basin. The roots shrink during dry periods. During the first event, the roots were dry and this enhanced macro-pore flow: the roots get saturated. Once the next event occurs the roots are saturated, and thus runoff initiation will occur. This is valid for events with precipitation between 14 and 31 mm and an I_{60} of above 12 mm h^{-1}.

Next to the dynamics of the basin, the root depth for the Caatinga biome is about 15% smaller in the dry season compared with the rainy season (Pinheiro, Costa, & de Araújo, 2013). The dynamics and seasonality of the basin will be further discussed in paragraph 2.1.

In this research there will be tried to find a way to simulate runoff initiation for the AEB. Since field measurements show the before mentioned dynamic behaviour, the models should be able to simulate that similar behaviour.

Several hydrological models will be run for 116 daily runoff events in the period from 2005 till 2014 (**Error! Reference source not found.**). After that the runoff data will be collected and validated. The main objective can be described as:

> ***The main objective of this bachelor thesis is to assess the specific validity of scientifically recognised hydrological models for application in the Caatinga biome, Northeast Region of Brazil, by analysing their ability to explain runoff initiation at the event scale.***

1.3 Research questions

For the reasons that have been discussed in the introduction and will be discussed in the background (paragraph 2.1), a research question can be presented:

> ***Given the observations that initial abstractions at the Aiuaba Experimental Basin are dynamic and seasonal, to which extent can models faithfully reproduce runoff initiation in an environment that has those dynamic initial abstractions?***

In order to answer the main research question, three sub-questions have been formulated. Together with the main research questions they will lead to the conclusions and recommendations of this thesis.

1) What are the best methods to show the comparison of the modelled runoff initiation outcomes and the measured results?
2) For which types of events (for example in terms of soil moisture and rainfall intensity) are the models best suited?
3) In which way is the variability of the effective root depth implemented into the hydrological models?

2 Research design

This chapter circumstantiates the set-up of the research. It starts with a paragraph about the background of the research, where the phenomena of root water uptake and runoff initiation will be treated. This gives an insight about the underlying theory and the motive for this research.

In the second paragraph the used models Dicasm and Wasa will be introduced. The third paragraph describes the methodology and finally in the fourth paragraph the objective functions to review the models will be introduced.

2.1 Background

2.1.1 Root water uptake

Feddes et al. (2001) are showing that water uptake of roots can be modelled in two ways. Those ways describe a local point of view; the water availability to the roots is shown in combination with soil and root characteristics. The first plant based approach considers a representative root presented as a tube or line that has certain absorption properties. The second hydrological based approach describes the root system as a sink that penetrates each layer of soil uniformly, though not necessarily with a constant strength throughout the root zone. The root systems of both used models will be further explained in paragraph 2.2.

In this research, the soil-water-plant system of hydrological models will be investigated. The water and sediment fluxes are really relevant physical processes in semi-arid regions. Those fluxes are depending on vegetation parameters like the effective root depth. Güntner and Bronstert (2004) showed that the effective root depth is one of the most sensitive parameters in water-scarce environments such as the Caatinga biome.

2.1.2 Runoff initiation

Runoff initiation describes whether there is a start of runoff or not. The threshold value for runoff to be interpreted as runoff initiation is zero millimetres per rainfall event. From now on, precipitation is given in millimetres and this is considered as millimetres per rainfall event.

Runoff initiation is shown as a formula in Equation 2-1.

$$RI_i = \begin{cases} 0, & Q_i \leq 0 \\ 1, & Q_i > 0 \end{cases}$$

Equation 2-1 Runoff initiation given for a runoff event i. The threshold value for runoff initiation is given as zero millimetres. The values for runoff initiation can also be interpret as 'false' in case of runoff initiation equal to 0 and 'true' in case of runoff initiation equal to 1.

This research also considers cumulative runoff initiation. This is the cumulative value of runoff initiation after a particular event for all events so far, whereas the events are sorted by a criterion like precipitation or rainfall intensity. For example, the cumulative runoff initiation for all events shown the number of events that have positive value for runoff. This number can be compared with the cumulative runoff initiation of the measured values. The formula cumulative runoff initiation is shown in Equation 2-2.

$$CRI_{crit,n} = \sum_{i=1}^{n} RI_{crit} \qquad i = 1,2,\ldots n$$

Equation 2-2 Cumulative runoff initiation. The subscript 'crit' refers to the criterion of sorting the rainfall events (ascending), and n is the number of events.

The effective root depth in the AEB, which is assumed to be representative for the Caatinga biome, is about 15% smaller in the dry season than in the rainy season. This enhances the soil macro-porosity flow in the dry season and suggests that the initial abstractions in the Caatinga biome are depending on the seasonality of the root system (Pinheiro, Costa, & de Araújo, 2013). This is the first indicator for the dynamic behaviour of the AEB.

De Figueiredo et al. (2015) have investigated the basin and have monitored among other things precipitation, soil moisture content, evapotranspiration, river discharges and reservoir water level. They conclude that runoff initiation at the AEB is dynamic. They found several events with similar precipitation, but those events did not always produce runoff. This is also shown in area 'R-2' in Figure 2-1.

In the period from 2005 till 2014 116 events with precipitation above 10 mm were measured in the AEB. The researchers have selected 11 hydrological variables and the runoff was statistically analysed against those variables. It was put into practice by plotting those variables (also shown in Figure 2-1).

After plotting those variables the selection criteria were established. For example, after field observations it was concluded that runoff always appears when precipitation was over 31 mm. Besides that, runoff did never appear for events with rainfall below 14 mm or for I_{60} below 12 mm h^{-1}. Data outside those boundaries is considered as valid, but runoff initiation is ambiguous and therefore subject of research.

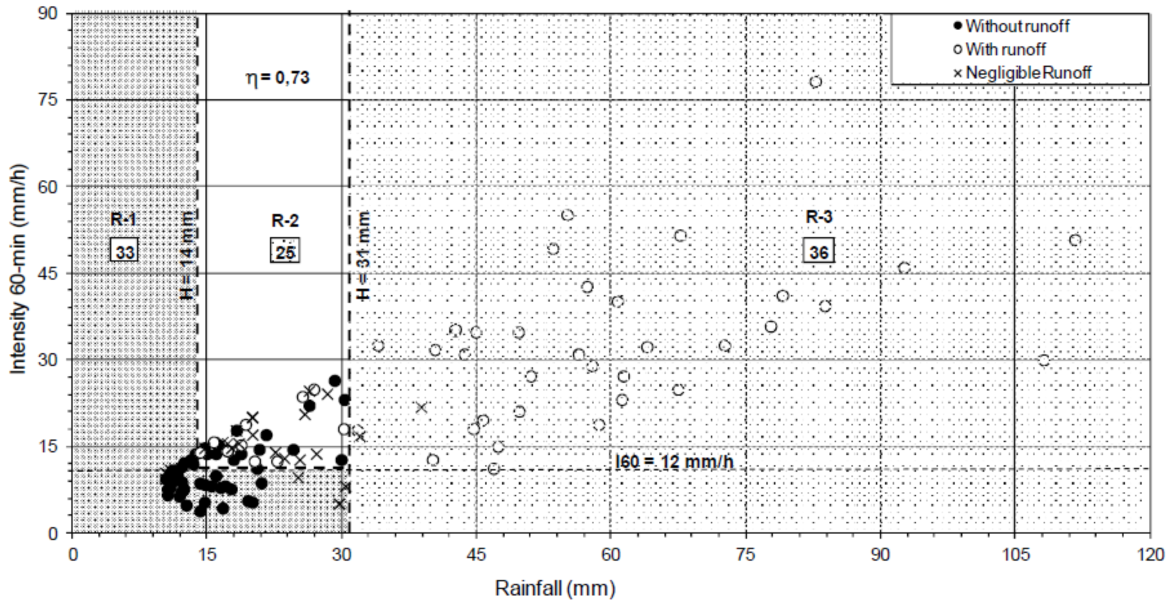


Figure 2-1 Data plotted for I_{60} versus precipitation, together with boundaries. Region 'R-1' shows rainfall events without runoff. In that same region no runoff events can be found. In region 'R-3' only runoff events and events with negligible runoff (<0.1 mm) can be found. Those regions do agree with the field measurements of de Figueiredo et al. (2015). However in region 'R-2' there is a mix of events with and without runoff (and negligible runoff). This cannot be explained by field observations. In that region, events can be found with both similar I_{60} and precipitation, but different runoff (initiation). Reprinted from "Runoff initiation in a preserved semi-arid Caatinga small watershed" by de Figueiredo et al, 2015.

The last step de Figueiredo et al. took was to determine the separation efficiency to assess the validity of the events for different combinations of variables (Equation 2-3).

$$\eta = \frac{N_N + N_R}{N_T}$$

η	Separation efficiency;
N_N	Number of no-runoff events within thresholds, without negligible runoff;
N_R	Number of runoff events within thresholds, without negligible runoff;
N_T	Total number of events, without negligible runoff.

Equation 2-3 The separation efficiency equation used by Figueiredo et al. (2015). In this case 'events within thresholds' include events that are in region R-1 and R-2.

Equation 2-3 can also be described as the percentage of events that can be explained by the threshold values of the used variables. For the AEB, runoff will never occur below thresholds for a certain precipitation and I_{60}. On the other hand there is also an upper threshold where runoff always will occur. However research has shown that there are also runoff events outside these thresholds. The separation efficiency is the amount of events that can be separated by the thresholds (region R-1 and R-3 in Figure 2-1) as a fraction of the total number of events (without negligible runoff of less than 0.1 mm).

The combination of variables that resulted in the highest separation efficiency was precipitation versus I_{60}. In that case 73% of the events could be explained by the criteria. Other combinations, e.g. soil moisture versus I_{60} (53%), were less able to explain runoff initiation.

To asses the current process of runoff iniation in the AEB the saturated hydraulic conductivity (Ksat) was measured on the riverbed, river banks and on hillslopes (179 samples). Ksat is a measure of the ease with which water can move through the soils (expressed in mm h^{-1}). The results have been presented in boxplots whereby the percentage of areas that allow runoff for every type of area within the basin is given. Higher precipitation will lead to higher percentages of area that allow runoff (for every type of area). After all it was concluded that indeed the threshold value for I_{60} of 12 mm h^{-1} is corresponding with the measured values for Ksat.

The most important conclusions that de Figueiredo et al. have made is that I_{60} actually is the most important variable to describe runoff initiation. The evaluated time of I_{60}, 60 minutes, is in good agreement with the concentration time of the basin (65 minutes). Besides that the threshold value for I_{60} (12 mm h^{-1}) is approximately equivalent to the river bank Ksat.

Precipitation versus I_{60} was still unable to explain runoff initiation in 27% of all events. Besides that is has been shown that runoff initiation in the basin is dynamic. Two events within the same period, with both the same antecedent soil moisture, are investigated. The first event had a higher precipitation and a higher I_{60} than a second event in the same period. However, only the second event did produce runoff. De Figueiredo et al. suppose that this is caused by the aforesaid dynamics of the roots; the roots shrink during dry periods, enhancing macro-pore flow and thus initial abstractions.

2.2 Descriptions of models

In this paragraph the used models during this research, Dicasm and Wasa, will be discussed. For both models there is in short background information and also the purpose and the operations of the models are explained. The used root systems are explained in a more detailed way.

2.2.1 Dicasm

The Integrated Hydrological Modelling System (IHMS) is developed to study the impacts of climate and land use changes on water resources. Dicasm (Distributed Catchment Marquette) is one of three sub-models and it deals with the unsaturated zone.

Dicasm has five components: (1) rainfall interception by crops and grass, (2) potential evapotranspiration, (3) surface runoff, (4) soil water balance of the unsaturated zone and (5) overland flow and channel flow routing.

The catchment area in Dicasm is divided into grid squares. In the AEB model it is divided in squares of 500 x 500 m^2. Runoff is routed between the low points of each grid square along the prevailing slope using a digital terrain model. The grid data contains for every grid an x-, y- and z-value. Besides that, for every grid the presence of a stream is given (different types).

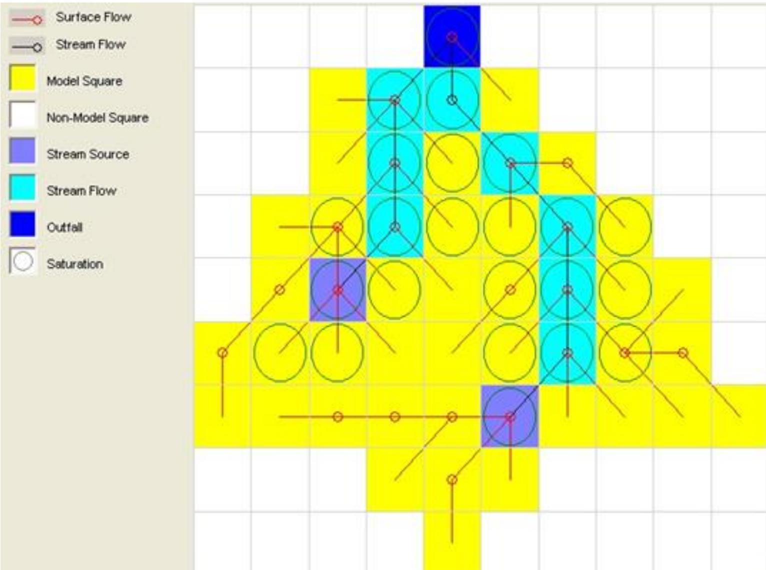


Figure 2-2 Stream and surface flow map of the AEB in Dicasm. The dark blue grid on top is the outfall from where runoff data is collected. The turquoise cells represent the stream flow that ends up in the outfall.

Soil properties are given in terms of wilting point, saturated water content, hydraulic conductivity and field capacity for every layer in every grid square. For every soil series the layers are provided.

Daily meteorological data consists of insulation, wind speed, vapour pressure and temperature. The rain files contain precipitation per grid for every day.

Runoff mechanism

The interception process within a cell of Dicasm is shown in Figure 2-3. The gross rain minus interception losses by crops and threes results in net rain. Together with surface runon from other cells net rain is the input for the runoff mechanism. A part of this input goes into the stream and this results in runon to other cells. The remaining water will be infiltrated into soils or will be stored. If there is infiltration excess or saturation excess, this water can run off to other cells.

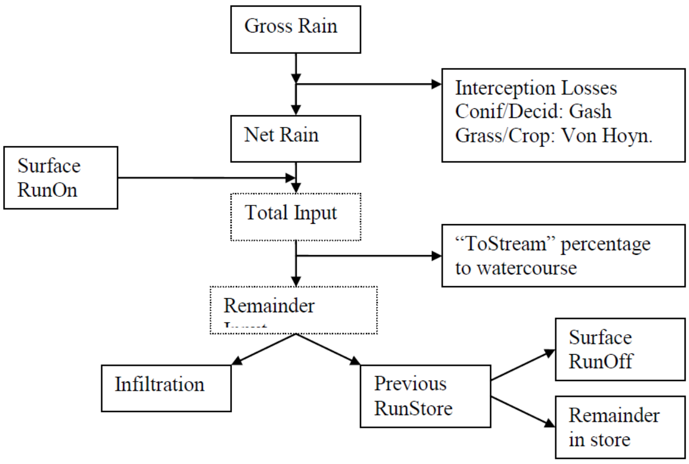


Figure 2-3 Interception process within a cell of Dicasm. Reprinted from "CEH Modelling Software: User Documentation" by Foster, 2012.

Infiltration excess is calculated according to the Green and Ampt (1911) equation. After the total infiltration F is found by Equation 2-4, the infiltration rate f can be obtained from Equation 2-5. Equation 2-5 can be solved by the method of successive substitution. A good start value for F is K times t. In both equations ψ is wetting front soil suction head, θ is water content and K is hydraulic conductivity.

Equation 2-4 Cumulative infiltration (volume) according to Green and Ampt (1911).

$$F(t) = Kt + \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right)$$

Equation 2-5 Infiltration rate according to Green and Ampt (1911).

$$f(t) = K\left(\frac{\psi\Delta\theta}{F(t)} + 1\right)$$

Surface runoff also depends on the surface conditions, soil moisture content and slope. A share of net rainfall will infiltrate in the soil surface. If not, all of the rainfall will be accommodated and the rest will pond and eventually run off as overland flow, which in some areas will find its way to the streams.

Dicasm uses The Four Root Layers Model (FRLM) of Ragab et al. (1997). The model describes the soil water movement in 4 different layers. Those layers represent each 25% of the total rooting depth. The inputs of the model contains effective rainfall and potential evapotranspiration.

If the inflow to a first layer exceeds its storage capacity, the excess water goes down to the second layer and so on. In the end the water available for infiltration will be dissipated within the four layers. The inflow for the first layer is the net rainfall.

The distribution of the water uptake depends on the root density distribution. Therefore the relative distribution is used which is determined by certain studies. For example most crops extract respectively 40%, 30%, 20% and 10% from the four quarters of the root zone. This is shown in Figure 2-4.

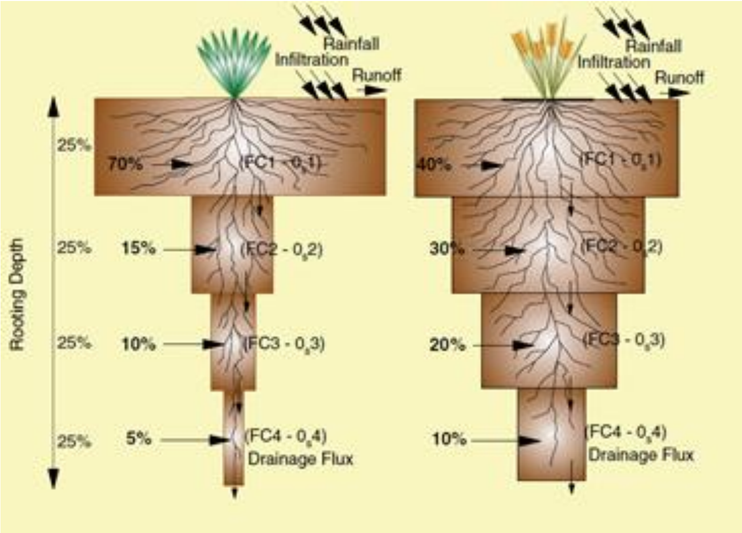
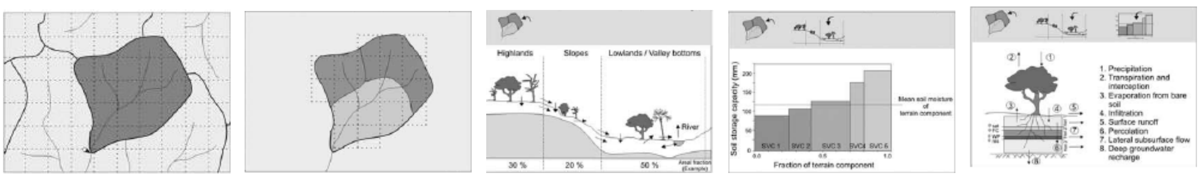


Figure 2-4 Plant water uptake with depth for crops and grass. Reprinted from "IHMS—Integrated Hydrological Modelling System. Part 1. Hydrological processes and general structure" by Ragab et al, 2010.

2.2.2 Wasa

The modelling framework WASA-SED (Model of Water Availability in Semi-Arid Environments) was developed for simulating water and sediment transport processes in large dryland catchments. It was developed as part of the SESAM project (Sediment Export from large Semi-Arid Catchments: Measurement and Modelling).

Wasa simulates among others runoff, erosion, transport processes of suspended and bedload fluxes and the retention and remobilization processes of sediment. The model is developed to simulate those processes for catchment areas up to ten thousands of square kilometres. The model works with five different levels of modelling units (Figure 2-5).



Catchment	Landscape unit	Terrain component	Soil-vegetation component	Profile

Figure 2-5 Levels of Wasa. Reprinted from "Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas" by Bronstert and Güntner, 2003.

Level 1 consists the catchment layer. The function of this level is to compute runoff routing. All the catchments are linked by a river network. Small reservoirs are represented by different classes, bigger reservoirs are calculated explicitly.

Level 2 describes the same catchment of level 1, but at this level the catchment is divided into areas with similar characteristics. The variability is describes for lateral and vertical processes. The areas are in general similar in lithology and bedrock characteristics. Also the shape of the surface is described: the hillslope length is taken into account as the difference in elevation between valleys and tops.

The terrain component is taken into account at level 3. Level 3 describes the variability of landscape characteristics in land units. Land units itself are divided into terrain components (level 4). Each land unit can consist at most three terrain components, characterizing tops, slopes and valleys.

Level 4 is the soil-vegetation component. Each component contains a specific combination of a soil type. That holds that the number of those components within in terrain component is given by the number of specific soil-vegetation combinations.

The last scale is level 5. Each soil-vegetation component (level 4) is described by a soil profile. For example the infiltration model of Wasa is given by the equations of Green and Ampt (1911, see also Equation 2-5 and Equation 2-6). The infiltration routine depends on the rainfall, minus interception, plus surface runoff from other units.

2.3 Methodology

For each model parameterization, running, validating and the first results of conclusions and recommendations will be accomplished. In this way difficulties during one of these steps can be experienced and be tackled, in order to complete the process for all models. The order of succession is shown in Figure 2-6 and will be discussed below.

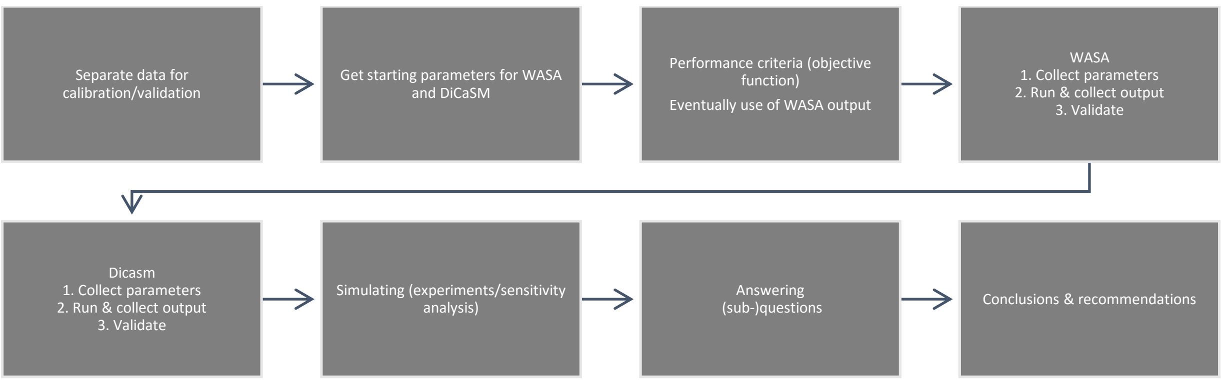


Figure 2-6 Flow diagram of the order of succession that was used during completing this thesis.

The first step of this research was to collect input data, which mainly consisted of events of rainfall and runoff initiation. This data was available for the period of 2005-2014. The models were already calibrated, so the complete dataset was used for validation.

The next step was to set up an objective function. It was useful to run the models first with another dataset and to set up the objective function experimentally.

The models had to be set up with the right parameters that describe the AEB in a correct way. For the WASA model calibrated parameters were yet available. Those parameters were also used in the Dicasm model.

After the models have been set up and calibrated, models have been run and output data was collected. The output consisted mainly of data that shows runoff for every submitted rainfall event. After that validation of the output has been done against data from the meters concerning the available methods for evaluating the models.

The validation results are being discussed and explained in a separate chapter. The differences of the models are explained and therefore some experiments have been done to explain the actual working of the models.

After the previous steps the conclusions and recommendations have been written down.

2.4 Methods to evaluate the results

In order to criticize the results that are generated by the models, several methods that are discussed below will be used. These methods will mainly be used to consider the results and will be useful to drawn up the conclusions and recommendations.

2.4.1 Cumulative runoff initiation curve

To show the runoff initiation of Wasa and Dicasm compared with the runoff initiation of the measured values, the cumulative runoff initiation curve is set up. Cumulative initiation is explained before in Equation 2-2.

To establish the runoff initiation curve the results first are ranked on a criterion. The criteria used in this research are I_{60} and precipitation (ascending). By sorting the events in this way, there can be showed that runoff initiation for both models and reality starts after a certain value of I_{60} or precipitation. For reality it has been shown by de Figueiredo et al. that when rainfall events are sorted by precipitation, the cumulative runoff initiation will start growing at the threshold value of 14 mm and will constantly grow for values greater than 31 mm.

The cumulative runoff initiation has been plotted versus the cumulative runoff initiation of the models. If the cumulative runoff initiation of the models show the same behaviour of the measured values, the models are able to reproduce runoff. In that ideal situation the curve would be similar to the identity line (y = x). The way of creating the cumulative runoff initiation curve is shown below in Figure 2-7.

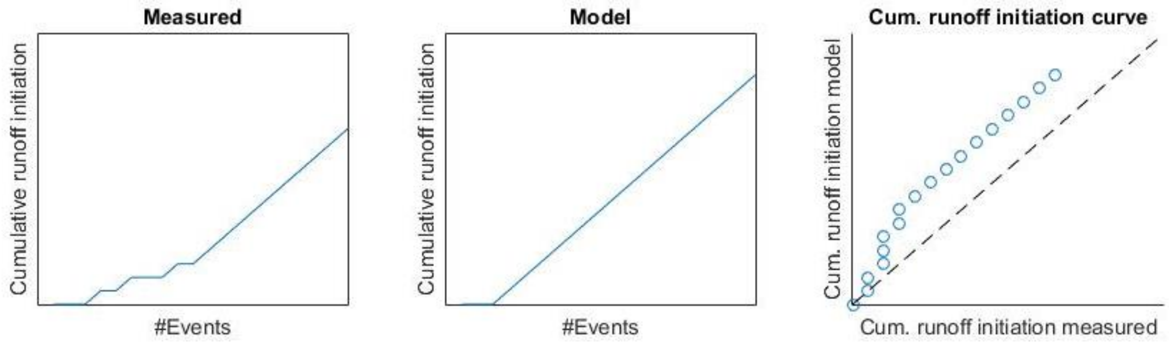


Figure 2-7 Generating the cumulative runoff initiation curve. First the cumulative runoff initiation for the measured values and models are collected (panel 1 and 2). Those are sorted on a criterion like precipitation or I_{60}. The next step is to plot the cumulative runoff initiation for the measured values versus the model values. In this example all the axes have equal length.

2.4.2 Coefficient of determination

The models will be run separately for every runoff event (see **Error! Reference source not found.** for the events). That holds that the events will be run after initial conditions of the model.

The output of the models contains the runoff for every imported event. After that with Equation 2-1 the value for runoff initiation and with Equation 2-2 the cumulative runoff initiation will be calculated. The cumulative amount of initiations will be compared with the cumulative measured initiations. The cumulative runoff initiation for both model and measured values will be determined by sorting the events by I_{60} and precipitation (both ascending).

The objective function is to maximize the coefficient of determination (Equation 2-6). This coefficient is determined by the residual sum of squares (RSS, nominator) and the total sum of squares (TSS, denominator). The RSS describes the unexplained variation; the discrepancy between measured values and model outcomes. This signifies that the coefficient of determination is the amount of unexplained variation in relation to the total variation.

$$R^2 = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2}$$

R^2	Coefficient of determination;
y_i	Cumulative initiation of the model for event i;
$\bar{y}$	Average cumulative initiation for all events;
f_i	Value of the measured cumulative initiation for event i.

Equation 2-6 Coefficient of determination.

2.4.3 Relative runoff curve

The relative runoff curve shows the runoff towards to the maximum value respectively for the measured values, Wasa and Dicasm. Therefore relative runoff has a value between 0 and 1. The x-axis contains the precipitation.

The result is a curve whereby all runoff curves for the measured values, Wasa and Dicasm are shown in the window. Next to that the moment from which runoff initiation starts can be distinguished, because the value of no runoff initiation is zero.

2.4.4 Contingency table

To show the frequency distribution of runoff initiation for the models compared with the observed initiations, a contingency table is used (Table 2-1). In that table the number of matches between initiations of the model and observed (measured) initiations can be compared. Since both modelled and observed initiations have 2 possibilities, the contingency table shows 4 combinations.

Table 2-1 Contingency table for runoff initiation.

		Number of observed (measured) initiations		
		Yes	No	Total
Number of modelled initiations	Yes	Right prediction (runoff initiation)	False prediction (model is overestimating runoff initiation)	Modelled yes
	No	False prediction (model is underestimating runoff initiation)	Right prediction (no runoff initiation)	Modelled no
	Total	Observed initiations	Observed no	All events

In the upper-left cell of Table 2-1 the number of events whereby both values for modelled and observed initiation are equal is shown. This means that the model is in agreement with the observations. The same applies to the lower-right cell, for events without runoff.

In the two remaining cells of the contingency table the number of events modelled initiations are not in agreement with the observed initiations. In the lower-left cell the number of events whereby the model has generated no runoff whether there was in reality, and in the upper-right cell the number of events whereby the model has generated runoff whether there was not in reality is given.

The objective is to maximize the number of correct positive initiations and correct negative initiations. Therefore the percentages of correct initiations and no-initiations will be calculated. Next to that all the 4 parts of the contingency table will be used to interpret the results.

2.5 Generating time series

The necessary input for the models is based on weather stations, measurements obtained at the AEB or on values that are used in earlier versions of the models. All the necessary input variables are given in Table 2-2 and will be explained below.

Table 2-2 Input variables of Wasa and Dicasm, with their corresponding units.

Variable	Unit	Needed for Wasa	Needed for Dicasm
Daily average temperature	°C	X	X
Daily average relative humidity	%	X	
Daily insolation	Hours		X
Daily average radiation	W m^{-2}	X	
Daily precipitation	mm	X	X
Length of rainy season	Days	X	
Wind speed	m s^{-1}		X
Vapour pressure	kPa		X
Initial water content	% of field capacity		X

Temperature, humidity and insolation data are retrieved from INMET BDMEP, weather station Campos Sales. Campos Sales is the closest weather station near the AEB and therefore will give reliable results. Temperature and humidity data both are daily averages.

Radiation data is retrieved from the used Wasa model, which uses monthly averages that have been measured over the years 2003 until 2008.

Rainfall data is abstracted from a rain gauge in the AEB. For every day the total amount of rainfall is accumulated, resulting in 116 rainfall events in the period of 2005-2014 (3652 days). Events with precipitation less than 10 mm have been neglected, because in reality they have never produced runoff. All 116 rainfall events are plotted in Figure 2-8 and Figure 2-9 (histogram).

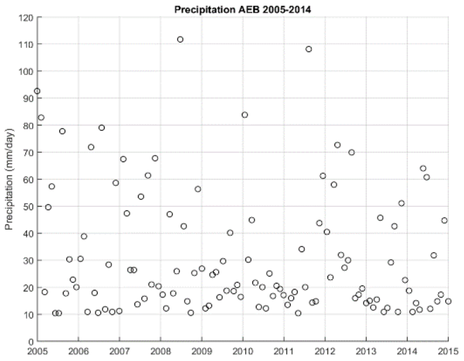


Figure 2-8 Precipitation sums for precipitation events in AEB 2005-2014. Retrieved from rain gauge in the AEB.

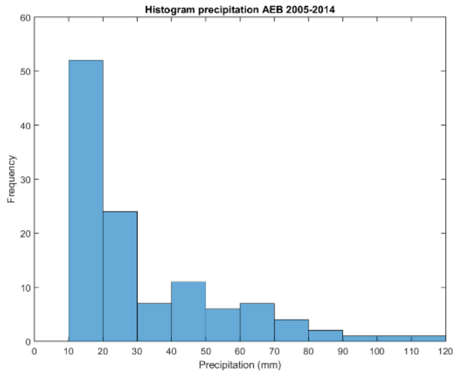


Figure 2-9 Histogram precipitation AEB 2005-2014. Retrieved from rain gauge in the AEB.

For every year, the start and end of the rainy season needs to be determined. This data is needed for the interpolation of the temporal distribution of vegetation characteristics (i.e. root depth) in Wasa. This is done by plotting the rainfall events. If the number of days between consecutive events was below the threshold value, it was added to the same rainy season. In this case, 150 days was a good threshold value. In Table 2-3 the first 10 dates of rainfall events are shown.

Table 2-3 Methodology to establish rainy season data.

Date	Number of days to next event	Comment
15-1-2005	5	Start of rainy season 1
20-1-2005	4	
24-1-2005	2	
26-1-2005	20	
15-2-2005	28	
15-3-2005	10	
25-3-2005	**255**	End of rainy season 1
5-12-2005	2	Start of rainy season 2
…	…	…

The resulting start and end dates for every year are shown in Table 2-4.

Table 2-4 Rainy season dates.

Year	Start date	End date	Length in days
2005	15/01/2005	25/03/2005	69
2006	05/12/2005	01/05/2006	147
2007	23/10/2006	02/05/2007	191
2008	20/01/2008	02/05/2008	103
2009	08/12/2008	30/05/2009	173
2010	02/01/2010	11/04/2010	99
2011	26/02/2011	09/07/2011	133
2012	03/01/2013	22/06/2013	170
2013	18/12/2013	18/03/2014	90

The average daily wind is retrieved from the Dicasm model of 2003-2008. In that model the wind varies from about 0.5 till 2.0 m s^{-1} with an average of 1.1 m s^{-1}. Wind data from INMET BDEP was also available, but this data had an average of about 5.0 m s^{-1} and therefore it seemed not to be suitable for applying in this case.

The vapour pressure is retrieved from the relationship between vapour pressure and temperature, used in the Dicasm model of 2003-2008. A polynomial fit is applied to the data and has resulted in Figure 2-10. The data fits well to the polynomial function ($R^2 = 0.99$).

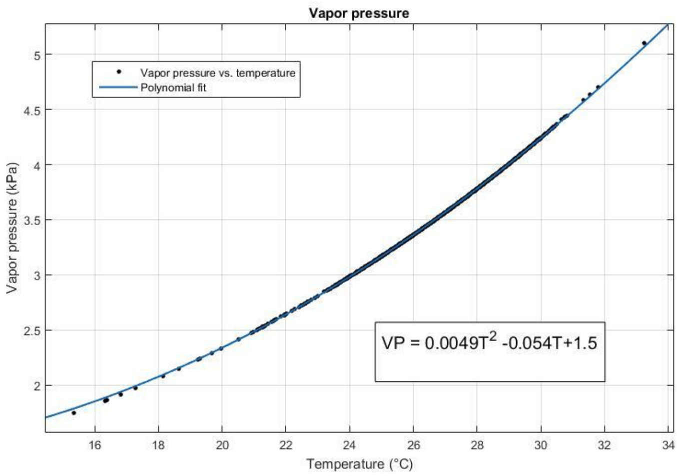


Figure 2-10 Vapour pressure vs. temperature of the Dicasm model 2003-2008. In the box the used equation for vapour pressure is given. VP = vapour pressure, T = average daily temperature.

If data for a particular day was not available, it has been completed by averages or zeros. In case of temperature (186 missing dates), humidity data (198 missing dates) and insolation (179 missing dates) the average of that particular month was taken. In case of missing precipitation it was set to zero.

The results of all the work abovementioned has led to time series for 2005-2014 for humidity, temperature, insulation and radiation (Figure 2-11).

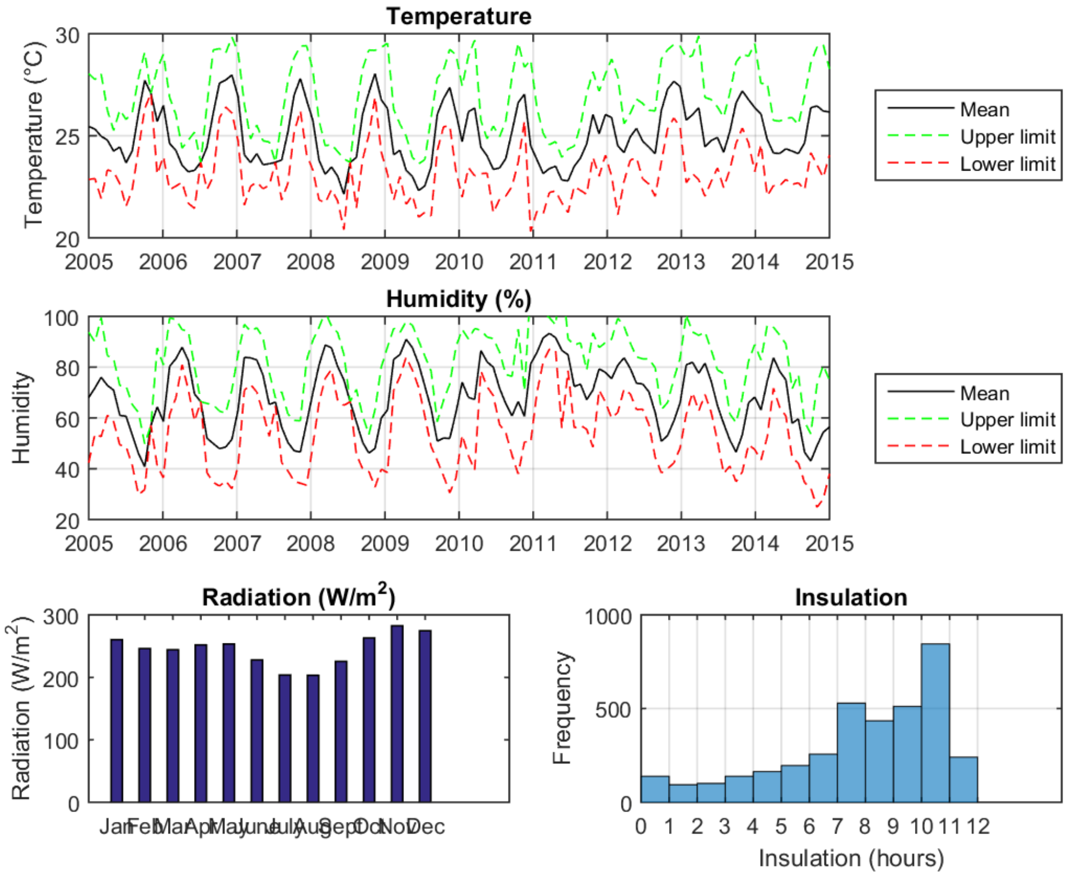


Figure 2-11 Monthly average radiation, temperature and humidity for 2005-2014. The upper and lower limits for temperature and humidity are given by a distance of two standard deviations from the mean.

The water content in the soils (soil moisture) is the amount of water that the soil can contain. The field capacity of a soil is the amount of water remaining in that particular soil after it has been wetted and after drainage has stopped. After that point the large pores are filled with both air and water. The smaller pores are still full of water. In the general it is supposed that the bigger the pores, the lower the field capacity (NRCCA, 2010). Saturated soil moisture content and field capacity for three locations in the AEB are given in Table 2-5.

Table 2-5 Field capacity & water content for the AEB.

Measuring point	Water content (m^3/m^3)	Field capacity (m^3/m^3)	SAT/FC (-)
1	0.437	0.276	1.6
2	0.529	0.220	2.4
3	0.414	0.117	3.5

The average SAT/FC for the AEB is around 2.5. Next to that for every rainfall event the soil moisture is measured. For this calculation the average soil moisture of three points is used. This value is on average 22% with a standard deviation of 6%. The soil moisture multiplied with the average SAT/FC value is the 'soil water percentage of the field capacity'. For every rainfall event measured antecedent soil moisture was available.

2.6 Running the models

For every of the 116 rainfall events in the period of 2005-2014 both models, Wasa and Dicasm, have been run after initial conditions. This means that in day 1 of the simulation the event was added and runoff data was collected after that particular day. For Wasa the simulation is done for 1 month because of practical reasons, however runoff data is collected after 1 day.

The necessary time series for Wasa and Dicasm are shown before in Table 2-2. These files were added to both models. Next to that for both models the parametrization that is done by researchers of the Federal University of Ceará is used. The parametrization for Wasa is the one used by Medeiros in 2009. For Dicasm the parametrization of Costa is used.

3 Results

In this chapter the results of both models will be discussed. The chapter discusses 4 methods of interpreting the results: (1) the cumulative initiation curve, (2) the relative runoff curve, (3) the coefficient of determination and (4) the contingency table (see paragraph 2.4). The outcomes of these 4 methods will be used to write down the next chapter, the conclusions.

In the period from 2005 until 2014 116 rainfall events have been measured. In that same period 67 runoff events have been observed. 22 events produced negligible runoff (<0.1 mm), this results in 45 significant runoff events.

With the same 116 rainfall events, Wasa produces 86 events and Dicasm even 116 events. In reality, the basin produces in 39% of the selected events runoff, Wasa 74% and Dicasm in 100% of the events. It can be concluded that in general Wasa and Dicasm are overestimating runoff initiation.

The fact that Dicasm is always producing runoff is being caused by the parameterization of runoff in the model (earlier explained in paragraph 2.2.1). In Figure 2-3 the interception process of Dicasm is given. The figure shows that net rainfall is used to run off (calculated with a base percentage), the remaining amount of water will infiltrate or will be stored. In case of infiltration excess or storage excess there will be an extra source for runoff. Because runoff data is collected after one day, storage capacity might not be reached and therefore only the base percentage is used.

3.1 Cumulative runoff initiation curve

In Figure 3-1 the cumulative runoff initiation curve for the results of Wasa and Dicasm is shown. This curve is drawn up according to paragraph 2.4.1.

The cumulative runoff initiation is calculated for Wasa and Dicasm, both sorted for precipitation and I_{60}. The figure shows that all 4 lines are above the identity line, this indicates that the models are overestimating runoff initiation over measured values. When the lines are starting to run parallel to the identity line indicates the point after which there is always runoff initiation. Both for Wasa and Dicasm this point starts earlier when sorting on precipitation instead of I_{60}. Therefore sorting on precipitation is a better method.

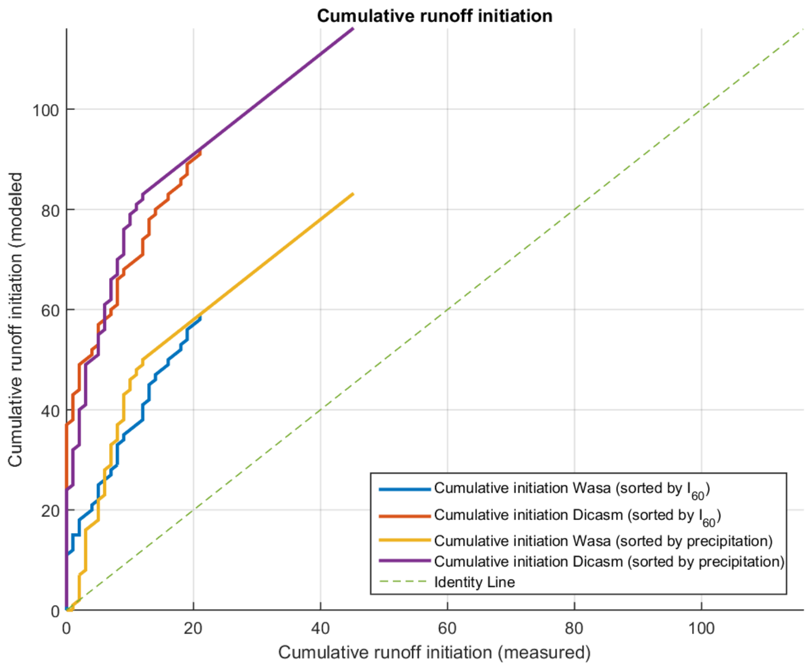


Figure 3-1 Cumulative initiation curve for Wasa and Dicasm. Both model results have been sorted on I_{60} and precipitation.

The cumulative runoff initiation curve is not the best way to interpret the results of Dicasm. Since Dicasm is producing runoff initiation for every rainfall event, the curves for Dicasm show the behaviour of reality. This means that the point from which the lines of Dicasm start running to be parallel, both Dicasm and measured values show always runoff.

Since the results of Wasa showing that the end point of the lines is not equal to 116 (the total number of events), that means that the model is not always producing runoff for every event. Therefore there is a point from which Wasa starts producing runoff. This point is 14.99 mm (when sorted on precipitation). In reality, the point from which there is always runoff is 30.40 mm. De Figueiredo et al. (2015) are showing that there is a 'grey zone' for runoff initiation between 14 and 31 mm. In that zone there is variable runoff initiation. The corresponding values for precipitation can be found in Appendix B.

The moment (after how many events) that initiations occur is important. This indicates the smallest rainfall event for which the model or reality is 'reacting'. However for some events runoff may stay out while for events with lower precipitation there is runoff initiation. This is the case in reality, not in Wasa. Therefore the precipitation height after which the initiations are continuous is the most important point. There the cumulative line is parallel to the identity line.

3.2 Coefficient of determination

The cumulative initiation for the Wasa model and measured values are plotted in Figure 3-2. In the plot top left 3 sections can be distinguished.

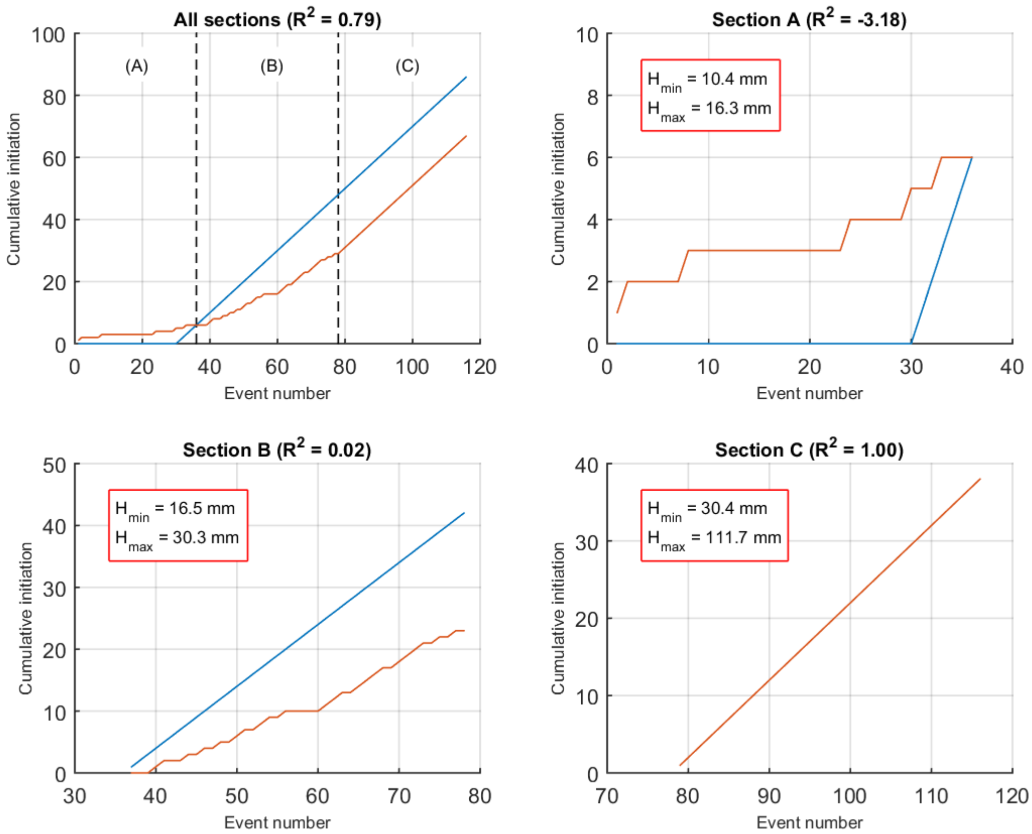


Figure 3-2 Coefficient of determination applied to the model outcomes of Wasa. The model outcomes have been converted to a cumulative runoff initiation (Equation 2-2). The blue line represents the results of Wasa and the red line shows the measured values.

In section A the cumulative initiation of Wasa is below the cumulative initiation of the measured values. This section has the worst coefficient of determination. Runoff initiation in Wasa starts after 30 events (precipitation 14.99 mm). After that point, for every event there is runoff generation. However, between event 1 and 79 (precipitation between 10.4 mm and 30.4 mm) for reality there is only sometimes runoff. After 35 events (precipitation 16 mm and further), there exists an equilibrium.

Section B starts in that equilibrium and stops whenever both lines are starting to act parallel. In section B there is always runoff initiation for Wasa, but not for reality. The R squared value is around 0, this holds a very weak relationship.

In section C there is runoff initiation both for Wasa and reality. This starts after 79 events and a precipitation of 30.4 mm. Obviously the R squared value is equal to one.

3.3 Relative runoff curve

In Figure 3-3 the (relative) runoff curve is presented. For all 116 events in the period from 2005 till 2014 of the AEB the relation between the relative runoff and the precipitation for the AEB, Wasa and Dicasm is shown. The runoff is presented as a fraction of the maximum value for runoff, since runoff depth of Wasa is much higher than Dicasm its runoff depth and the measured values. This is a method to show the results in one graph.

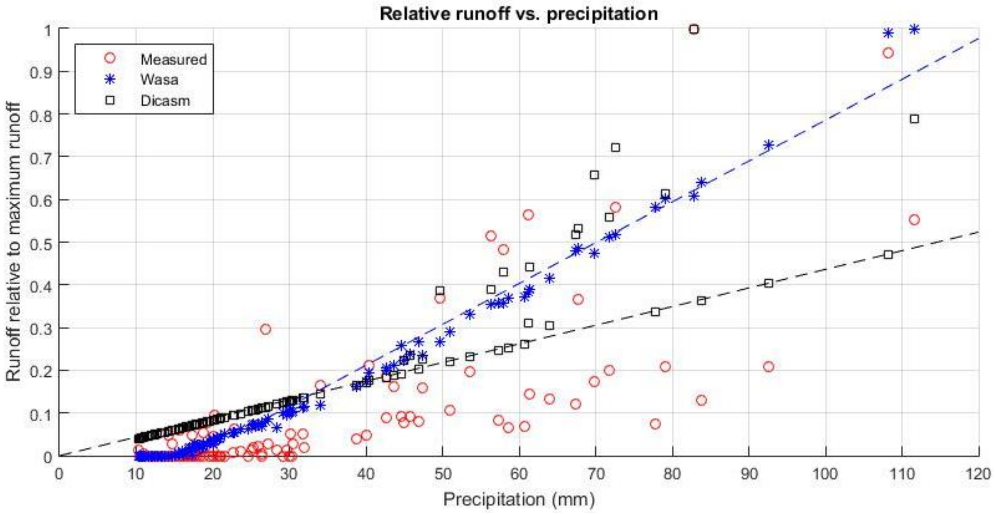


Figure 3-3 Relative runoff curve for measured values, Wasa and Dicasm.

The relation between precipitation and (relative) runoff for Wasa is smooth. For runoff until 15 mm it never produces runoff and from that value on the runoff is proportional to the precipitation. The dashed blue line shows the curve for Wasa for precipitation above 15 mm. The relation between runoff and precipitation is considered as linear.

For Dicasm runoff is also considered as linear. For events up to 47 mm the relation is linear, with a start in the origin. This relation is also valid for some events above 47 mm, however not all. This is caused by the use of the rational method for Dicasm, where runoff is proportional to runoff intensity. However for larger events Dicasm uses an extra exponential term. This is done because the rational method did not always give good results. This is already discussed in paragraph 2.2.1.

It can be concluded that the relation between precipitation and runoff for Wasa and Dicasm is (partially) smooth, and this relation for reality is more scattered. That indicates that reality is more complex than the current application of Wasa is showing. For reality it is more difficult to show from where runoff initiation is starting.

In Figure 3-3 two areas can be distinguished. In reality until 31 mm runoff initiation is dynamic. For both areas, under and above precipitation of 31 mm, there have been attempts to explain the behaviour of the results.

As earlier mentioned in paragraph 2.1.2 runoff initiation, especially for low magnitude events, can be explained by separating events on I_{60}. In Figure 3-4, the left panel, the measured values are separated by an I_{60} of 12 mm h^{-1}. This gives good results, because the figure shows that almost all events in that specific region have an I_{60} below 12 mm h^{-1}. Next to that almost all events in the upper region have a value for I_{60} above the threshold value.

It also appears that for the second section of Figure 3-4, the differing runoff can be separated in two areas by sorting the events on antecedent soil moisture. In Figure 3-4 the lower part of the section above a precipitation of 31 mm are events with soil moisture below 0.26 and the upper part is above that value. Therefore it can be concluded that Wasa and Dicasm can better predict events with higher antecedent soil moisture.

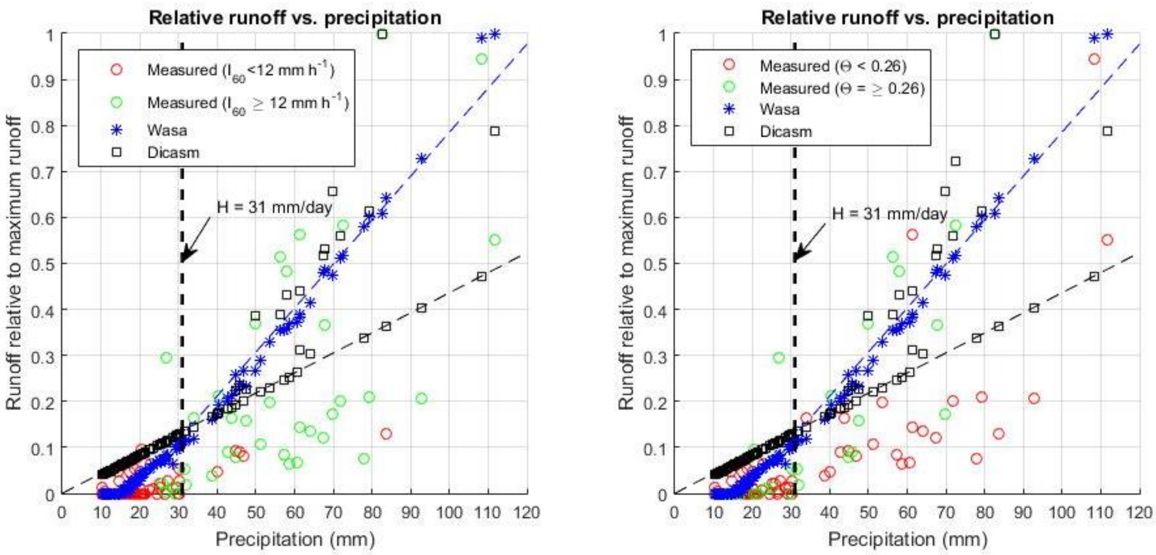


Figure 3-4 Relative runoff, separated in two areas with a precipitation threshold value of 31 mm. The left figure shows that most measured values left of the dashed line have an I_{60} value below 12 mm h^{-1}. Furthermore, the values on the right of the dashed line have an I_{60} value above 12 mm h^{-1}. Therefore the behaviour of the measured values in the zone with a precipitation below 31 mm can be explained by I_{60}. However on the right hand of the dashed line the measured values are more spread. This region can better be explained by antecedent soil moisture content. For a relative runoff up to 0.2 most values have an antecedent soil moisture below 0.26. For a relative runoff of over 0.2 most measuring points have an antecedent soil moisture over 0.26. Therefore antecedent soil moisture seems an important indicator for runoff initiation in the region of precipitation above 31 mm per event.

3.4 Contingency table

In Table 3-1 the contingency table of the results of Wasa is shown. On the basis of this table several remarks can be made.

The first remark is that in only 1 out of 45 events Wasa is not showing runoff initiation, while in reality there actually was. The other 44 events showed that runoff in reality was also shown by the model.

In case of no measured runoff (67 events), in around 37% (29) of the events Wasa agreed with that observation. As mentioned before in paragraph 2.1.2, in reality runoff initiation is dynamic for events between 14 and 31 mm (concerning negligible runoff) and it produces never runoff below precipitation of 14 mm. However, Wasa generates for every event from 15 mm runoff.

Table 3-1 Contingency table for all events in Wasa.

Wasa	Number of observed initiations			
Number of modelled initiations		Yes	No	Total
	Yes	44	42	86
	No	1	29	30
	Total	45	67	116

The contingency table for the results of Dicasm is not shown. This is because the model produces always runoff, even for events with lower than 10 mm. This is earlier explained in paragraph 2.2.1.

Because Wasa is generating runoff for every event above 15 mm, a dataset with a lot of events above that value and less with a lower value, the percentage will give a distorted view. Therefore the contingency table is also drawn up for events up to 31 mm (Table 3-2). This is the value for which in reality there is always runoff.

Table 3-2 Contingency table for Wasa with events with precipitation below 31 mm.

Wasa	Number of observed initiations			
Number of modelled initiations		Yes	No	Total
	Yes	9	39	48
	No	1	29	30
	Total	10	68	78

In Table 3-2 is shown that 78 out of 116 events have precipitation below 31 mm. Only 10 of these events have produced significant runoff. These are the values closer to the border of 31 mm. However, in the cases that in reality there was no measured runoff (68 out of 78), Wasa produces in 39 cases runoff. In total 9 + 29 = 38 events in this region are predicted well, roughly 50% out of 78.

4 Conclusions

In this report the (sub-) questions have already been partially answered, but in this chapter they will be further discussed and summarized. The main research question was: 'to which extent can models faithfully reproduce runoff initiation in an environment that has dynamic initial abstractions'? Therefore the main objective of this research is to validate the models Wasa and Dicasm concerning runoff initiation.

Both models give more of less a smooth relationship between precipitation and runoff (initiation), the results from reality are more scattered. Next to that both models are overestimating runoff initiation as well. Wasa produces for every event within the AEB runoff for precipitation over 15 mm, Dicasm produces runoff for even very small precipitation.

In Dicasm the infiltration and water store mechanisms seem not to be used, the base percentage is used. This formula is not suitable to show any dynamics and cannot distinguish runoff initiation. This might be caused by the short run time of just one day, whereby the more extensive systems that are used by Dicasm are not considered.

The contingency table in the results shows that for all events Wasa agrees in 37% of the cases. For events up to 31 mm 38 out of 78 (roughly 50%) of the runoff initiation is predicted correctly.

It can be concluded that the used models do not consider the aforesaid dynamic behaviour, for events with similar precipitation the runoff (initiation) is also similar.

The first sub-question is: "What are the best methods to show the comparison of the modelled runoff initiation outcomes and the measured results?". In this research the best method to show the results is the contingency table. Since runoff is considered as initiation and not as runoff depth, methods that show the results in terms of depths do not really add anything of substance to the discussion since they are significant higher. Next to that, the contingency table can be set up for different groups of precipitation, whereby it can be useful to discuss the results in that specific range.

The second sub-question is: "For which types of events (for example in terms of soil moisture and rainfall intensity) are the models best suited?". Figure 3-4 shows that the progress of the relative runoff depths can be approached by separating the events. Rainfall events up to 31 mm can be distinguished by a threshold value of I_{60} of below 12 mm h^{-1}. In the upper region, it is harder to separate the events. The best guess is to explain their behaviour with antecedent soil moisture over or under 0.26.

The last two sub-questions have partially answered the last one: "In which way is the variability of the effective root depth implemented into the hydrological models?". It seems that there is no seasonal variability in the modelled root systems and thus runoff initiation is not sensitive to that phenomenon because the output shows a smooth relationship whereas reality is more scattered.

5 Discussion and recommendations

The first concern that can be made about the results is that runoff is considered as initiation and not in runoff depth. Therefore it might be that initiation results for the models are valid, but the depths are not and vice versa. Therefore it might be useful to calibrate the models first with respect to runoff depths and after that validate the initiations.

The time step that is used in both models is daily. For both models it is possible to put hourly rainfall data, therefore it is worthwhile to investigate how the models cope with that time step. Next to that the models are also run for just one day. Therefore the results are highly depending on initial conditions. It might be useful to run the events as time series, for example with a variable number of days between the events.

In this research the input variables are adjusted for every event. However only the daily precipitation seems an important parameter for producing runoff initiation. Since the results (for example in Figure 3-3) show that the relationship of the models are very smooth and only have a small deviation, there can be concluded that the variability of the meteorological data (except for precipitation) does not have a big influence on the results. Therefore in the future it might be easier and not less accurate to use average values. The sensitivity of the variables should also be investigated on forehand.

According to de Figueiredo et al. (2015) runoff initiation depends a great deal on the root system and its dynamic and seasonal behaviour. This system is very fine meshed and needs further investigation. Besides that the bandwidth of precipitation (between 10 and 31 mm) for where runoff initiation is uncertain is very small.

The system that is introduced by de Figueiredo et al. is more complex than laboratory researches and also not suitable for small experiments. The equations that are used in the models to simulate runoff and other processes are based on laboratory research, but the dynamics (macro pores) are more complex. Therefore there should be searched for a way to implement this.

Bibliography

de Figueiredo, J. V., de Araújo, J. C., Medeiros, P. H., & Costa, A. C. (2015). *Runoff initiation in a preserved semi-arid Caatinga small watershed, Northeastern Brazil.*

Feddes, R., Hoff, H., Bruen, M., Dawson, T., de Rosnay, P., Dirmeyer, P., . . . Pitman, A. (2001). Modeling Root Water Uptake in Hydrological and Climate Models. *Bulletin of the American Meteorological Society*, 2797-2809.

Foster, A. (2012, October). CEH Modeling Software: User Documentation.

Günter, A., & Bronstert, A. (2004). Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. *Journal of Hydrology*, 136-161.

Güntner, A. (2002). *Large-scale Hydrological Modelling in the Semi-Arid North-East of Brazil* . Potsdam.

Hidrosed. (2011, January 1). *HIDROSED*. Retrieved from Grupo de Pesquia Hidrosedimentológica do Semiárido: http://www.hidrosed.ufc.br/index.php/en/

Hidrosed. (s.d.). *Hidrosed* . Fonte: Hidrosed: http://www.hidrosed.ufc.br/index.php/en/history

INMET. (2015). *Banco de Dados Meteorológicos para Ensino e Pesquisa.* Fonte: Instituto Nacional de Meteorologia: http://www.inmet.gov.br/portal/index.php?r=bdmep/bdmep

NRCCA. (2010). *Competency Area 2: Soil hydrology AEM.* Retrieved from Northeast Region Certified Crop Adviser: http://nrcca.cals.cornell.edu/soil/CA2/CA0212.1-3.php

Pinheiro, E., Costa, C., & de Araújo, J. (2013). Effective root depth of the Caatinga biome. *Journal of Arid Environments*, 1-4.

Ragab, R., & Bromley, J. (2010). IHMS—Integrated Hydrological Modelling System. Part 1. Hydrological processes and general structure. *Hydrological processes*, 2663-2680.

Ragab, R., Bromley, J., Dörflinger, G., & Katsikides, S. (2010). IHMS - Integrated Hydrological Modelling System. Part 2. Application of linked unsaturated, DiCaSM and saturated zone, MODFLOW models on Kouris and Akrotiri catchments in Cyprus. *Hydrological Processes*, 2681-2692.

Ragab, R., Finch, J., & Harding, R. (1997). Estimation of groundwater recharge to chalk and sandstone aquifers using simple soil models. *Journal of Hydrology*, 19-41.

Rijksoverheid. (2015, August 12). *Reisadvies Brazilië*. Retrieved from Rijksoverheid: http://www.rijksoverheid.nl/onderwerpen/reisadviezen/brazilie

Stowa. (June de 2010). *Hydrologische onzekerheid - samenvatting.* Fonte: Stowa: http://www.stowa.nl/Upload/publicaties/STOWA%202010%2016%20(Samenvatting)%20LR.pdf

The World Bank. (2015). *World DataBank*. Fonte: The World Bank: http://databank.worldbank.org/

UNESCO. (14 de March de 2012). *Global water resources under increasing pressure from rapidly growing demands and climate change, according to new UN World Water Development Report*. Fonte: UNESCO Media Services: http://www.unesco.org/new/en/media-services/single-view/news/global_water_resources_under_increasing_pressure_from_rapidly_growing_demands_and_climate_change_according_to_new_un_world_water_development_report/#.VdrzYfbtmko

WHYCOS. (s.d.). *Need for WHYCOS*. Fonte: World Hydrological Cycle Observing System: http://whycos.org/whycos/about-whycos/need-for-whycos

Appendix A Terms of reference

Universidade Federal do Ceará

Terms of reference of bachelor's thesis

These are the terms of reference of the bachelor's thesis of Jelger Hoeksma, from the University of Twente, in the Netherlands, to be developed in collaboration with the Hidrosed Research Group of the Federal University of Ceará, Brazil.

Background. There is a lack of knowledge about hydro-environmental parameters of the Caatinga biome, located in the semi-arid North-eastern Brazil, including the soil-water-plant system. It was recently found that the effective depth of the Caatinga roots is 15% smaller in the dry season compared with that of the rainy season, which enhances the soil macro-porosity flow in the dry season (Pinheiro et al. 2013[1]). Besides, field data of the Aiuaba Experimental Basin (AEB; 12 km^2; preserved Caatinga vegetation) for the decade 2005 – 2014 showed that the classical hydrological approach could not explain runoff initiation in 27% of the events. Figueiredo et al. (submitted[2]) concluded that the initial abstractions in this biome are strongly influenced by the root-system seasonality, which changes macro-porosity flows.

Scientific question. Given the assumptions that (i) initial abstractions at AEB are dynamic and seasonal; and that (ii) most hydrological models do not tackle this issue; we ask: 'to which extent can models faithfully reproduce runoff initiation in an environment that has dynamic initial abstractions'?

Goals. The main objective of this project is to validate three scientifically recognised hydrological models concerning runoff initiation at the event scale in the Caatinga biome, Brazil.

Methodology. The selected hydrological models for this task are HEC-HMS[3], WASA[4] and DICASM[5]; which will be applied to the 444 monitored events at the Aiuaba Experimental Basin for the period of 2005 – 2014. Models will be parameterized for the basin; then executed for the events; and, finally, analysed statistically. In order to support a consistent discussion, the physical initial-abstraction approach of each model will be investigated.

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[1] Pinheiro EAR et al. (2013) Effective root depth of the Caatinga biome. Journal of Arid Environments 89, 1 – 4
[2] Figueiredo JV et al. (submitted) Runoff initiation in a preserved semi-arid Caatinga small watershed, Northeastern Brazil
[3] US Army Corps of Engineers (2000) Hydrologic Modeling System HEC-HMS. Technical Reference Manual
[4] Güntner A, Bronstert A. (2004) Representation of landscape variability and lateral redistribution processes for large scale hydrological modelling in semi-arid areas. Journal of Hydrology 297, 136–161
[5] Ragab R, Bromley J (2010) Integrated Hydrological Modelling System. Part 1. The hydrological processes and general structure, Hydrological Processes 24 (19), 2663-2680

Appendix B Events and model outcomes

Event Number	Date	Precipitation (mm)	Runoff Wasa (m³)	Runoff AEB (m³)	RI Wasa	RI AEB	CRI Wasa	CRI AEB
1	15/03/2005	10.37	0	360	FALSE	TRUE	0	1
2	25/03/2005	10.40	0	350	FALSE	TRUE	0	2
3	17/01/2010	10.41	0	0	FALSE	FALSE	0	2
4	16/03/2008	10.62	0	0	FALSE	FALSE	0	2
5	21/04/2006	10.62	0	0	FALSE	FALSE	0	2
6	01/02/2007	10.89	0	0	FALSE	FALSE	0	2
7	04/04/2013	10.92	0	0	FALSE	FALSE	0	2
8	05/04/2006	10.92	0	100	FALSE	TRUE	0	3
9	05/06/2013	10.92	0	0	FALSE	FALSE	0	3
10	24/06/2012	10.92	0	0	FALSE	FALSE	0	3
11	16/02/2007	11.16	0	0	FALSE	FALSE	0	3
12	18/12/2013	11.68	0	0	FALSE	FALSE	0	3
13	23/10/2006	11.90	0	0	FALSE	FALSE	0	3
14	30/01/2014	11.94	0	0	FALSE	FALSE	0	3
15	14/04/2008	12.17	0	0	FALSE	FALSE	0	3
16	25/01/2008	12.17	0	0	FALSE	FALSE	0	3
17	22/04/2009	12.19	0	0	FALSE	FALSE	0	3
18	03/01/2013	12.42	0	0	FALSE	FALSE	0	3
19	10/03/2012	12.45	0	0	FALSE	FALSE	0	3
20	13/04/2009	12.70	0	0	FALSE	FALSE	0	3
21	29/04/2008	13.20	0	0	FALSE	FALSE	0	3
22	27/05/2009	13.46	0	0	FALSE	FALSE	0	3
23	14/04/2007	13.71	0	0	FALSE	FALSE	0	3
24	21/02/2012	14.22	0	1278	FALSE	TRUE	0	4
25	22/06/2013	14.22	0	0	FALSE	FALSE	0	4
26	29/03/2010	14.22	0	0	FALSE	FALSE	0	4
27	15/03/2008	14.73	0	0	FALSE	FALSE	0	4
28	09/02/2014	14.73	0	0	FALSE	FALSE	0	4
29	02/04/2010	14.73	0	0	FALSE	FALSE	0	4
30	18/03/2014	14.73	0	758	FALSE	TRUE	0	5
31	05/03/2012	14.99	173	0	TRUE	FALSE	1	5
32	20/03/2012	15.49	6653	0	TRUE	FALSE	2	5
33	19/04/2007	15.74	4061	1632	TRUE	TRUE	3	6
34	09/07/2011	16.00	7949	0	TRUE	FALSE	4	6
35	30/05/2009	16.00	6048	0	TRUE	FALSE	5	6
36	08/12/2008	16.26	346	0	TRUE	FALSE	6	6
37	02/04/2009	16.51	6480	0	TRUE	FALSE	7	6
38	25/04/2009	16.76	11750	0	TRUE	FALSE	8	6
39	09/05/2009	17.02	14256	0	TRUE	FALSE	9	6
40	20/01/2008	17.26	605	148	TRUE	TRUE	10	7
41	17/02/2012	17.27	13046	1255	TRUE	TRUE	11	8
42	10/02/2014	17.27	14256	0	TRUE	FALSE	12	8
43	07/12/2005	17.70	21773	0	TRUE	FALSE	13	8
44	12/02/2008	17.74	14602	116	TRUE	TRUE	14	9
45	19/04/2006	17.96	19872	0	TRUE	FALSE	15	9
46	24/01/2005	18.26	15638	673	TRUE	TRUE	16	10
47	02/01/2010	18.29	19181	0	TRUE	FALSE	17	10

48	03/03/2009	18.55	17194	396	TRUE	TRUE	18	11
49	01/05/2013	18.80	18317	0	TRUE	FALSE	19	11
50	19/02/2009	18.80	22810	1428	TRUE	TRUE	20	12
51	04/05/2009	19.30	21254	2095	TRUE	TRUE	21	13
52	19/02/2012	19.56	26352	0	TRUE	FALSE	22	13
53	18/02/2006	20.05	28685	1223	TRUE	TRUE	23	14
54	27/01/2010	20.07	21773	281	TRUE	TRUE	24	15
55	20/04/2009	20.07	30758	0	TRUE	FALSE	25	15
56	02/05/2007	20.30	27216	2552	TRUE	TRUE	26	16
57	01/05/2009	20.57	33091	0	TRUE	FALSE	27	16
58	18/03/2009	20.83	31882	0	TRUE	FALSE	28	16
59	25/04/2007	21.06	35942	0	TRUE	FALSE	29	16
60	10/04/2009	21.59	39830	0	TRUE	FALSE	30	16
61	26/04/2013	22.61	42250	183	TRUE	TRUE	31	17
62	06/02/2006	22.81	43891	1702	TRUE	TRUE	32	18
63	28/02/2011	23.62	50803	241	TRUE	TRUE	33	19
64	30/04/2008	24.60	50112	0	TRUE	FALSE	34	19
65	23/04/2009	25.15	55901	359	TRUE	TRUE	35	20
66	26/03/2008	25.34	58234	537	TRUE	TRUE	36	21
67	02/05/2008	25.64	54605	1934	TRUE	TRUE	37	22
68	17/02/2008	25.89	57715	603	TRUE	TRUE	38	23
69	07/04/2007	26.40	55555	0	TRUE	FALSE	39	23
70	23/03/2007	26.40	60998	146	TRUE	TRUE	40	24
71	07/04/2008	26.90	63936	7898	TRUE	TRUE	41	25
72	18/04/2011	27.18	67824	758	TRUE	TRUE	42	26
73	18/11/2006	28.40	52013	318	TRUE	TRUE	43	27
74	04/01/2013	29.21	79920	0	TRUE	FALSE	44	27
75	21/01/2009	29.72	75514	340	TRUE	TRUE	45	28
76	03/05/2011	29.97	83030	0	TRUE	FALSE	46	28
77	04/04/2009	30.23	81821	1378	TRUE	TRUE	47	29
78	05/02/2006	30.32	78970	0	TRUE	FALSE	48	29
79	20/03/2006	30.42	83462	763	TRUE	TRUE	49	30
80	04/02/2014	31.75	88646	1399	TRUE	TRUE	50	31
81	13/04/2011	32.00	91757	514	TRUE	TRUE	51	32
82	25/01/2010	34.04	94867	4391	TRUE	TRUE	52	33
83	23/03/2006	38.86	128390	1023	TRUE	TRUE	53	34
84	02/03/2009	40.13	137117	1253	TRUE	TRUE	54	35
85	26/02/2011	40.39	153101	5675	TRUE	TRUE	55	36
86	09/03/2008	42.63	158976	2383	TRUE	TRUE	56	37
87	26/03/2013	42.67	164074	4987	TRUE	TRUE	57	38
88	09/04/2010	43.68	168566	4355	TRUE	TRUE	58	39
89	11/02/2014	44.70	204422	2466	TRUE	TRUE	59	40
90	06/04/2009	44.95	177293	2067	TRUE	TRUE	60	41
91	26/03/2012	45.72	188698	2427	TRUE	TRUE	61	42
92	01/02/2008	46.93	212112	2178	TRUE	TRUE	62	43
93	20/02/2007	47.41	185760	4256	TRUE	TRUE	63	44
94	26/01/2005	49.70	212458	9913	TRUE	TRUE	64	45
95	19/04/2013	51.05	230947	2878	TRUE	TRUE	65	46
96	18/04/2007	53.53	262138	5290	TRUE	TRUE	66	47
97	01/04/2008	56.38	282442	13822	TRUE	TRUE	67	48

98	15/02/2005	57.32	283219	2221	TRUE	TRUE	68	49
99	01/03/2011	57.91	283824	12932	TRUE	TRUE	69	50
100	14/02/2007	58.64	294106	1755	TRUE	TRUE	70	51
101	23/12/2013	60.71	295315	1813	TRUE	TRUE	71	52
102	11/04/2010	61.21	304992	15126	TRUE	TRUE	72	53
103	22/04/2007	61.38	310349	3851	TRUE	TRUE	73	54
104	20/12/2013	64.01	330739	3594	TRUE	TRUE	74	55
105	18/02/2007	67.47	381542	3276	TRUE	TRUE	75	56
106	29/04/2007	67.69	386726	9829	TRUE	TRUE	76	57
107	05/05/2011	69.85	377136	4639	TRUE	TRUE	77	58
108	09/04/2006	71.86	406598	5366	TRUE	TRUE	78	59
109	05/03/2011	72.64	411178	15585	TRUE	TRUE	79	60
110	05/12/2005	77.79	461981	2013	TRUE	TRUE	80	61
111	01/05/2006	79.10	478829	5578	TRUE	TRUE	81	62
112	20/01/2005	82.77	484186	26814	TRUE	TRUE	82	63
113	03/04/2009	83.82	510106	3445	TRUE	TRUE	83	64
114	15/01/2005	92.65	578189	5556	TRUE	TRUE	84	65
115	21/03/2010	108.20	787536	25302	TRUE	TRUE	85	66
116	27/02/2008	111.67	795485	14800	TRUE	TRUE	86	67