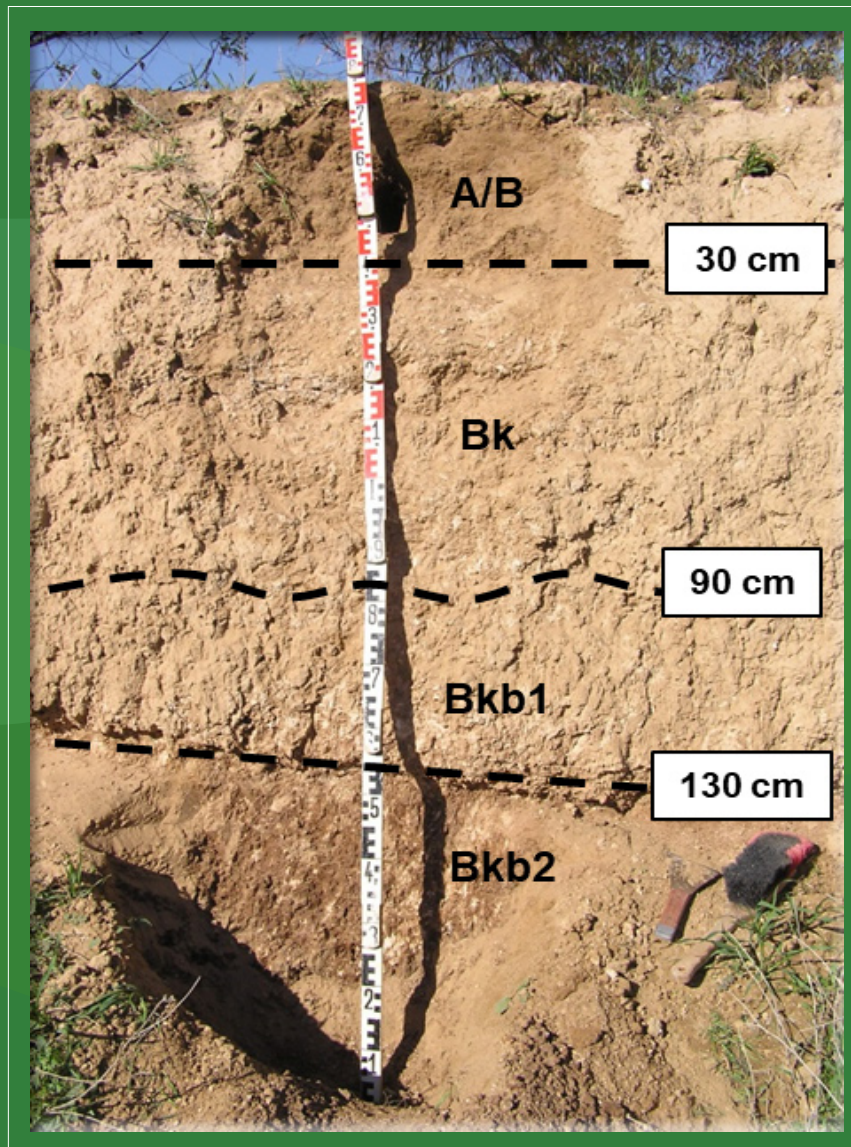




Geological Survey of Israel
Ministry of Energy

Control of climate properties on long term soil water distributions in semi-arid and arid soils with implications on pedogenic salts

Tali Horowitz



© Published by the Geological Survey of Israel
32 Yeshayahu Leibowitz St. Jerusalem, 9692100 Israel

Front cover picture:

Soil profile described near Mishmar HaNegev, northern Negev (mean annual rainfall of 240 mm) showing a clear calcic horizon (Bk) at 30-90 cm depth. This depth corresponds to the general trend of decreasing depth to Bk horizon with increasing mean annual rainfall as described in the Negev by Dan and Yaalon (1982).

Back cover picture:

Monitoring station in Gilat: soil water sensors (with yellow cables) and CO₂ sensors (grey cables) installed into the undisturbed trench wall. The trench was covered after installation. The sensors were connected to a data logger that sent the measured data to the GSI on a daily basis. A weather station was established outside of the trench.

Cover design: Tirza Tzuberi



Geological Survey of Israel
Ministry of Energy

Control of climate properties on long term soil water distributions in semi-arid and arid soils with implications on pedogenic salts

Tali Horowitz

This thesis was submitted in partial fulfillment of the requirements for the degree of "Master of Science" to the senate of the Hebrew University of Jerusalem.

The study was carried out under the supervision of:

Dr. Onn Crouvi, Geological Survey of Israel.

Prof. Efrat Morin, The Hebrew University of Jerusalem.

Acknowledgements

I would like to acknowledge and express my gratitude for the funding that was provided by the Geological Survey of Israel and the Institute of Earth Sciences for my education at the Hebrew University of Jerusalem; and to the United States-Israel BSF who funds this research. I am most appreciative of my advisors Dr. Onn Crouvi and Prof. Efrat Morin who have provided me with this opportunity to further my education, have offered encouragement and advice throughout this period, and have introduced me to new perspectives, multiple research tools, and with a fascinating combination of disciplines. Special thanks to Dr. Ravid Rosenzweig who helped to shape this research from a soil scientist point of view; to Mr. Uri Malik whose contribution to the technical issues and actual installation of the monitoring stations was crucial for the research; and to Miss Yael Jacobi-Glass who analyzed the soil samples, along with Mr. Guy Tau that introduced me to the correct protocols and offered help with preparation of the samples.

I am additionally thankful for the researchers and colleagues that helped develop my understanding of Quaternary geology research, the physical and chemical processes occurring in natural soil environments, and of data analysis and modelling which was required for the completion of this work. They include Dr. Francesco Marra, Dr. Anton Vaks, Dr. Avner Ayalon, Prof. Alon Angert, Prof. Naftali Lazarovitch, Prof. Shmuel Assouline, Prof. Aaron Yair, Prof. Yehouda Enzel, and Prof. John Prueger. In addition, to my committee members, Prof. Alon Angert and Dr. Yoseph Yechieli.

I also would like to thank my family, friends, and colleagues for the constant support and encouragement over the last three years. Lastly, I would like to thank my partner, Dudi Dorham, for being so understanding of my crazy work schedule and for offering his constant advice and unyielding support.

Abstract

Rainfall is the main driver for translocation of solutes in soils. In arid and semi-arid regions, carbonate and gypsum are accumulated in shallow soil horizons as a consequence of high evaporation and low rainfall. Depths to carbonate horizons are frequently used to reconstruct paleo mean annual rainfall as it has been shown that the two are positively correlated. Although other climatic properties also affect this correlation, such as intra-annual rain properties, they were rarely examined in the past. In this thesis I couple a compartment model for infiltration together with a stochastic weather generator to simulate long-term soil wetting depth distributions in soils of the northern Negev, Israel.

The mean wetting depth, and depths where cumulative water fluxes are 30% of the total rainfall correlates with depths to carbonate horizons and therefore may serve as their proxies. My simulations show that the proxies trend with mean annual rainfall. However, varying other weather properties to simulate weather in other regions or periods can produce a great scatter of up to 75 cm. Mean event depth is much more important variable than mean annual rainfall for the depths of the proxies. For the same annuals, correlations with mean event depth, or the number of annual rain events reduced the scatter from 75 to 25 cm at the most. The effects of changes in weather properties on depths of the proxies grow with increase in annual rainfall and decrease in mean evaporation at the rainfall season and vice-versa. Local sensitivity for a 20% shift in weather parameters in the northern Negev, Israel suggests that effects of any single weather property cannot be significant in areas where mean annual rainfall < 200 mm/year. The potential evapotranspiration greatly affects both the trends and the depth of the proxies, and therefore different rainfall seasonality can cause great differences between depths to Bk horizons in areas with the same annual rainfalls. Effects of dry spells and extreme rainfalls versus mean weather properties should be tested against specific weather scenarios. For soils with greater sand-silt compositions, the effects of the climate properties mentioned above would be even greater. The results here are also available in units of soils' water holding capacities and therefore may be translated to depths in other soils as well. Other potential proxies for depth to gypsic horizons were found to be more sensitive to climate variations. To conclude, I have introduced an approach to study long term soil water dynamics and its relationship with climate properties and soil horizons. I quantify how deeper carbonate horizons may be as a result of increased mean annual rainfall, lower evapotranspiration, or having fewer, but more intense storms. The results of my study can improve interpretations of past climates that are based on properties of buried calcic and gypsic horizons. This framework allows for investigation of climate effects on other water distribution properties as well, and could lead to important conclusions regarding effects of future climate change on water availability to vegetation and vertical movement of pollutants or fertilizers in soils.

Table of content

List of figures	vi
List of tables	vii
List of Appendices	vii
List of variables and symbols	vii
Preface	1
1 Background	2
1.1 Climate properties and depths to saline soil horizons	2
1.2 Climate control on water wetting depth in soil	5
1.3 Models of water balance in soil	7
1.3.1 Water Distribution in soil	7
1.3.2 Rainfall Generator	9
1.3.3 PET Generator	10
2 Goals	12
3 Study site	13
3.1 Current climate in the northern Negev.....	14
3.2 Monitoring site	15
4 Materials and methods.....	17
4.1 The compartment model.....	17
4.1.1 Soil space in the model	17
4.1.2 Infiltration and downward flow	18
4.1.3 Evaporation procedure and soil water content test for AET	18
4.1.4 Model parametrization	20
4.1.5 Proxies for depths to Bk and By horizons	20
4.2 The weather generator.....	21
4.2.1 The rainfall generator.....	23
4.2.2 The PET generator.....	25
4.3 Sensitivity analysis.....	26
5 Results	28
5.1 The compartment model.....	28
5.1.1 Soil Texture.....	28
5.1.2 Analyses of water content retrieved from monitoring stations	30
5.1.3 Calibration-validation.....	31
5.1.4 Water distribution properties	31
5.2 The Rainfall Generator	34

5.3	PET Generator	38
5.4	Geographical trends of water distribution properties and MAR.....	39
5.5	Sensitivity analysis for carbonate and gypsum proxies	40
5.5.1	Local sensitivity	40
5.5.2	Global sensitivity analysis.....	44
6	Discussion	48
6.1	WD proxies for depths to Bk and By horizons	48
6.1.1	Validation of the framework	48
6.1.2	Proxies have different sensitivities to extremes vs. mean trades of weather	48
6.1.3	Proxies for depths to Bk horizons	49
6.1.4	Proxies for depth to By horizons	50
6.2	Effects of weather properties on the Bk horizons proxy and its trends.....	51
6.2.1	Variability of weather and the scatter of the results	51
6.2.2	Effects of seasonality on trends and correlations of depths to Bk horizons and MAR..	51
6.2.3	Effects of intra-seasonal rainfall distribution properties on trends and correlations of depths to Bk and MAR.....	52
6.2.4	Interpretations of weather scenarios from depths to Bk horizons: local effects of weather properties on depth to Bk horizons at specific locations	53
6.3	Steps required for further refinement of the model and analysis	54
6.3.1	Limitations of the analysis.....	54
6.3.2	Calibrated parameters in Gilat and assumptions made for simulations in other sites..	56
7	Conclusions	58
8	References	60
	Hebrew Abstract	86

List of figures:

Figure 1	Depths of salts accumulation zones in the soils of Israel (After Dan and Yaalon, 1982)	2
Figure 2	Global record of depths to (a) Bk and (b) By soil horizons and the mean annual rainfall	3
Figure 3	Correlations of (a) depths to Bk with MAR and (b) with calculated mean depth of water penetration (Arkley ,1963) for sites with with winter seasonality in California and Nevada, western US.	9
Figure 4	Map of the study site with spans of salts horizons and mean annual rainfall isopachs	13
Figure 5	Intra-annual variance of the mean daily evaporation in 4 meteorological stations in the Negev	15
Figure 6	Soil profiles with Bk horizons in the study site: (a) from Gilat monitoring station and (b) from the near-by Mishmar-HaNegev (MN) site described by Dr. Onn Crouvi (GSI)..	16
Figure 7	The compartment model scheme (modified after Marion et al, 1985).	18
Figure 8	HYDRUS 1D simulation of water content profiles over the rainfall season of 2016/17 in Gilat – most changes in water content are restricted to the first 1m of the soil profile.....	19
Figure 9	The rainfall generator scheme for 1 year of synthetic data generation.	23
Figure 10	Schem for deriving probability Gaussians from measured rainfall data for the probabilities of generating rain days (PWAU and PWAD) with the rainfall generator in this study.....	24
Figure 11	A scheme of the combine weather and soil models is presented here to illustrate the control of weather parameters: A, B, Fd, Fw and FPET on weather properties and the results of the compartment model (i.e.-depths to Bk and By proxies)	26
Figure 12	Soil textures of samples from profiles of Gilat and Sde Boker and Mishmar Ha-Negev.	28
Figure 13	Results of the compartment model calibration and validation for optimal parameters in Gilat	31
Figure 14	Initial results of the compartment model predict association of soil water distribution properties with depths to Bk in Sde Boker, Gilat and Be'eri.....	32
Figure 15	Rainfall generator validation for Gilat: Distributions of mean annuals and daily depths of 100 synthetic series compared with measured rainfall series in Gilat.	34
Figure 16	Local sensitivity and correlations between rainfall parameters and mean rainfall properties.....	36
Figure 17	Validation results of the rainfall generator in Be'er-Sheva and Be'eri – examples of the model's performance for un-calibrated locations in the study site	38
Figure 18	Validation of the PET generator: comparison of monthly means and standard deviations of measured and synthetic daily PETs.	38
Figure 19	Tred of depths to Bk/By in Israel reproduced by WD results of the compartment model simulations - using long term synthetic weather for 4 sites in the Negev	39
Figure 20	Local sensitivities of MeanWD to 20% change in the model's weather parameters.....	42
Figure 21	local sensitivity - Max absolute difference (in %) of Bk proxies and rainfall distribution properties to 20% changes in weather parameters.....	42
Figure 22	Effects of 20% change in weather parameters on the regional trend of MeanWD with the mean annual rainfall.	43
Figure 23	Local effect of rainfall parameters on the trending of MeanWD with the mean annual rainfall suggesting differences in the trending of depth to carbonate horizons for areas with different climates	43
Figure 24	Global sensitivity analysis: results of proxies for depths to Bk and By calculated with various weather scnarios – plotted against mean annual rainfall	44
Figure 25	Effect of means of: events per year, events depths and annual rainfall on trends and depths of MeanWD carbonate horizon proxy.....	45
Figure 26	Effects of rainfall distribution properties with similar mean annual rainfalls on MeanWD.....	46
Figure 27	Effect of mean events per year on MeanWD carbonate horizon proxy for limited range of annual rainfall	47

List of tables:

Table 1	Mean Rainfall properties of data sets from 4 meteorological stations in the study site.	14
Table 2	Ranges of rainfall parameters included in the simulations for global analysis	27
Table 3	Soil samples from Gilat monitoring station profile: lab results and Rossta water holding parameters predictions.....	29
Table 4	Soil samples from Sde boker monitoring station profile: lab results and Rossta water holding parameters predictions.....	29
Table 5	Gilat monitoring station : soil samples and sensors measured water contents.....	30
Table 6	Sde Boker monitoring station : soil samples and sensors measured water contents	30
Table 7	Local sensitivities of the three potential Bk proxies to the calibrated parameters – results from simulations for rainfall of Gilat meteorological station.	33
Table 8	Verification of the rainfall generator in Gilat: statistics of measured (IMS) and synthetic rainfall properties comaprered.....	35
Table 9	Functional relationships of rainfall generator parameters with mean rainfall properties....	37

List of Appendices:

Appendix I	List of definitions and variables	65
Appendix II	Description of the soil profile of 'Gilat' monitoring station	68
Appendix III	Description of the soil profile of 'Sde Boker' monitoring station	71
Appendix IV	Compartment model parametrization: soil samples, monitoring data and calibration procedure	73
Appendix V	Test statistics of the synthetic rainfall data series	78
Appendix VI	Effects of weather parameters on depths of Bk proxies and on mean weather properties.....	82
Appendix VII	Results of global sensitivity for Index30 proxy.....	85

List of variables and symbols

WDs	wetting depths- a conceptual term describing the distribution of depths of soil wettings by rainfalls. See also WD in Model Loggers further down this list.
MAR	mean annual rainfall (mm/year)

Soil Horizons

Bk	illuvial soil horizon in with secondary carbonate precipitated to form carbonate nodules (American Soil Science nomenclature)
By	illuvial soil horizon in which secondary gypsum was precipitated (American Soil Science nomenclature)

Water Contents in soils- conceptual definitions

FC	maximal water holding capacity of the soil against gravity (cm^3/cm^3)
WP	minimal water holding capacity of the soil against transpiration (cm^3/cm^3)
θ_r	minimal water holding capacity of the soil against evaporation (cm^3/cm^3)
WHC	the difference between maximal and minimal available soil water contents - usually: $\text{FC} - \text{WP}$, here was taken as: $\text{FC} - \theta_r$ (cm^3/cm^3)

Evapo-Transpiration

PET	the potential evapo-transpiration (mm/day), is depended only in the atmospheric energy demand.
AET	actual evapo-transpiration (mm/day), is depended in PET and in the available water content of the soil profile
Kc	Crop coefficient (unit-less): conceptual and semi-empiric assessment of vegetation effect that limit evapo-transpiration rates.

Prescribed parameters for the AET procedure in the compartment model (Eq.1)

T.M.Depth	Effective soil depth for evapotranspiration processes. Ratio of the total moisture in the soil profile to the WHC of the profile is taken at depth range of 0-T.M.Depth to determine the daily AET according to WHCIndex In this study it was assumed as the top 1m of the soil.
WHCIndex	Ratio of the mean soils' WHC range that determines transition from an AET which is controlled by the atmospheric demanded ($\text{AET} = \text{Kc} * \text{PET}$) or an AET that is controlled by the available soil water content (decreases with TotalMoisture). This is an empirical parameter that was retrieved from field measurements in California. It was taken at 0.546 according to Marion et al. (1985).

Model Loggers of soils' long-term water dynamics

WD	wetting depth (cm) is the maximal depth of water income to the soil after rain - logged as a daily depth.
WaterFluxOut	amount of water that proceeds downward flow from each compartment - logged as an array of cumulative water contents (cm^3/cm^3) for each compartment
WetZone	cumulative days in which a compartment is filled to its maximal capacity of FC water content (days) - logged as an array

WD and flux Proxies for depths to Bk and By

MeanWD	average depth of daily wetting depth (cm) - indicates depth to Bk
SMeanWD	average depth of the maximal wetting depths per season (cm) - indicates depth to By
WDp80	80th percentile of daily wetting depths (cm) - indicates depth to Bk
SWDp80	80th percentile of the maximal wetting depths per season (cm) - indicates depth to By
Index30	soil depth at which WaterFluxOut =30% of the total simulated rainfall (cm) - indicates depth to Bk
Index3	soil depth at which WaterFluxOut =30% of the total simulated rainfall (cm) - indicates depth to By

Weather generator definitions day types and distributions

Wet Day	day with rain depth of 0.1 mm or more.
Dry day	day with no rain or up to the lower limit of measured depth of 0.1 mm
WAW day	wet after wet day - a day within rainfall event. In the rainfall generator - WAW was assigned with probability of occurrence according to the day in the year; in the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
WAD day	wet after dry day - the first day in a rainfall event of one day or longer. WAW was assigned with probability of occurrence according to the day in the year; in the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
DAW day	dry after wet day - the first day after a rain event stopped (first in a dry spell). In the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
DAD day	dry after dry day - a day within a dry spell. In the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
PWAD	probability of a WAD day occurring for each day of 365 day's year - representing probability for starting a rain event according to the time in the year. Empirical data was fitted with a Gaussian.
PWAW	probability of a WAW day occurring for each day of 365 day's year - representing probability for continuing of a rain event according to the time in the year. Empirical data was fitted with a Gaussian.

Input parameters that control weather properties

Fd	input parameter to the rainfall generator controlling frequency of events per year: a factor over PWAD Gaussian
Fw	input parameter to the rainfall generator controlling duration of events: a factor over PWAU Gaussian
A	input parameter to the rainfall generator, mostly controlling the mean daily depth. this is the scale parameter of the daily depth Weibull distribution function (mm)
B	Input parameter to the rainfall generator, mostly controlling the extreme daily depth. This is the shape parameter of the daily depth Weibull distribution function (--)
F_{PET}	input parameter to the compartment model in order to simulate higher/lower PET or Kc. This is a factor over the daily PET time-series.

Rainfall distribution properties (intra-annual)

EventsN	mean frequency of events* (events/year): calculated from a distribution of annual number of events.
EventsDurations	mean event* duration (days/event): calculated from a distribution of all event durations in the record or simulation.
EventsDepth	mean event* depth (mm/event): calculated from a distribution of all event durations in the record or simulation.
DailyDepth	mean daily depth (mm) - calculated from a distribution of all daily depths (not an annual mean) in the record or simulation.

* a rainfall event is defined as 1 or more consecutive days with daily rainfalls > 0.1mm

Preface

Climate is the main driver of vertical water flow in the soil that in turn controls vegetation dynamics, soil forming processes, transport rates of mobile materials, and drainage potentials. In arid and semi-arid regions soils' wetting depths (WD) are limited due to low rainfall and high evaporation rates, which results in shallow accumulations of salts in the soil. Thus, horizons of accumulated salts are thought to be markers of the climate regime that created them. Our knowledge on soil water distribution and salt accumulation in soils originates from two very different approaches that use different time scales: a) long term correlations between average climate properties (e.g. average annual rainfall) and depth to calcic, gypsic, and salic horizons that are well known and widely used; and b) physical modelling of soil water dynamics during a single rainfall event. However, there is a limited understanding on how intra-annual variations in climate properties (e.g. seasonality) affect soil water distribution and hence salts accumulation in soils on long term scales. The goal of this study is to quantify changes and variability in climate properties on the long term wetting distributions in arid to semi-arid soils that can be used as a proxy for the depth of pedogenic salt accumulation. The main tool for this research is a modelling framework that includes stochastically simulating rainfall and evaporation. With this tool I examined how different properties of climate affect the spatial and temporal variation in WDs. The study area is the northern and central Negev desert that exhibits rainfall gradient and soils with calcic and gypsic horizons.

1 Background

1.1 Climate properties and depths to saline soil horizons

Climate is one of the main drivers of soil forming processes. Rainfall infiltrates the soil carrying solutes from which secondary minerals form within the soil profile. High concentrations of salts form clear soil horizons, e.g. calcic horizon (termed as Bk horizon) and gypsic horizon (termed as By horizon) that seem to portray the depths of rainwater penetration to the soil profile (Arkley, 1963; Birkland, 1984; Retallack, 2005), and therefore can be used to learn about past climates. The term WD is used here to define these depths of soil wetting and will be discussed further in the next subsection. For the purpose of this research, one WD is the depth of water distribution from a daily rainfall.

In arid and semi-arid regions, soils' WDs are limited due to low rainfall and high evaporation rates, and shallow Bk horizons are common. Gypsum accumulates in deeper layers than carbonates because of its higher solubility. Depth to By horizons is thought to reflect WDs of wetter years or extreme rainfall, while depth to Bk horizons seem to reflect WDs of average years or normal rainfall (Dan and Yaalon, 1982). Bk horizons are also limited by the existence of vegetation (Amit *et al.*, 2006) and are associated with the base of the root zone and biological activity (Schlesinger, 1985). This is because respiration creates a CO₂ gradient in shallow layers of the soil which in turn affects the solubility of CaCO₃.

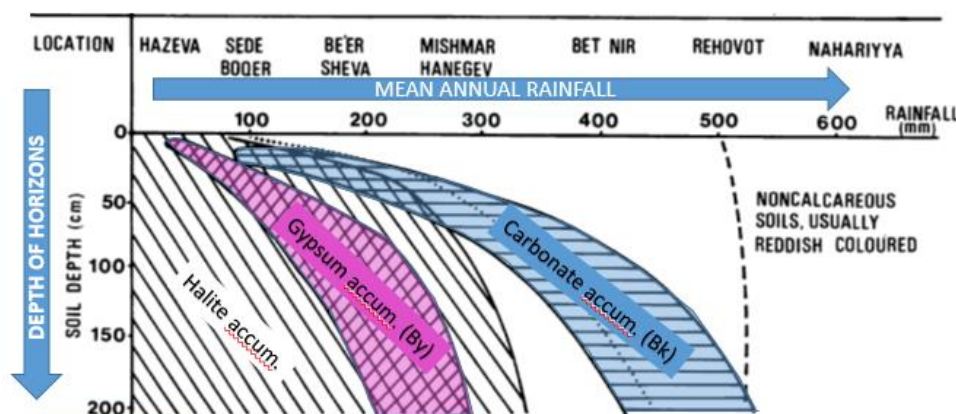


Figure 1 Depths of salts accumulation zones in the soils of Israel. The zones trend with the mean annual rainfall (After Dan and Yaalon, 1982).

Although vegetation plays a clear role in the development of calcic horizons, rainfall and its resultant WDs are still considered prominent factors in determining the depth to Bk horizons, as they both affect the depths of eluviation, and depths of biological activity in

the soil (Cohen, 1982; Liao, 2006; Piedallu *et al.*, 2013; Tabor and Myers, 2015). The fact that the depths to Bk and By horizons are controlled mostly by rainfall is manifested by the correlations between depth to Bk and By horizons and mean annual rainfall (MAR) (Figures 1,2).

Suggestions were made to derive paleo-climate functions from these relationships (Jenny and Leonard, 1934; Arkley, 1963; Retallack, 1994, 2005; Retallack and Huang, 2010). If it is robust and simple to implement, these relationships would represent a powerful paleo-precipitation indicator. However, the usage of depths to calcic and gypsic horizons for interpretations of past MAR is debatable, mainly because of lack of a clear universal trend between the two (Royer, 2000). While for regions with similar climate properties - such as seasonality - the two variables are well correlated (Jenny and Leonard, 1934; Arkley, 1963), these trends are different for different regions (Figure 2.a). This can explain the scatter of global data (Figure 2). The relationship of global data with MAR is far from being injective, especially for most of Bk and By horizons which form in the upper 1 m of the soil: having 50-100cm range of depths to Bk/By horizons for the same annuals, and about 650 mm/y range of MAR for the same depths to Bk horizons. The scatter may result from differences in climate properties, vegetation and soil characteristics. The former is the least to be discussed in the context of these correlations.

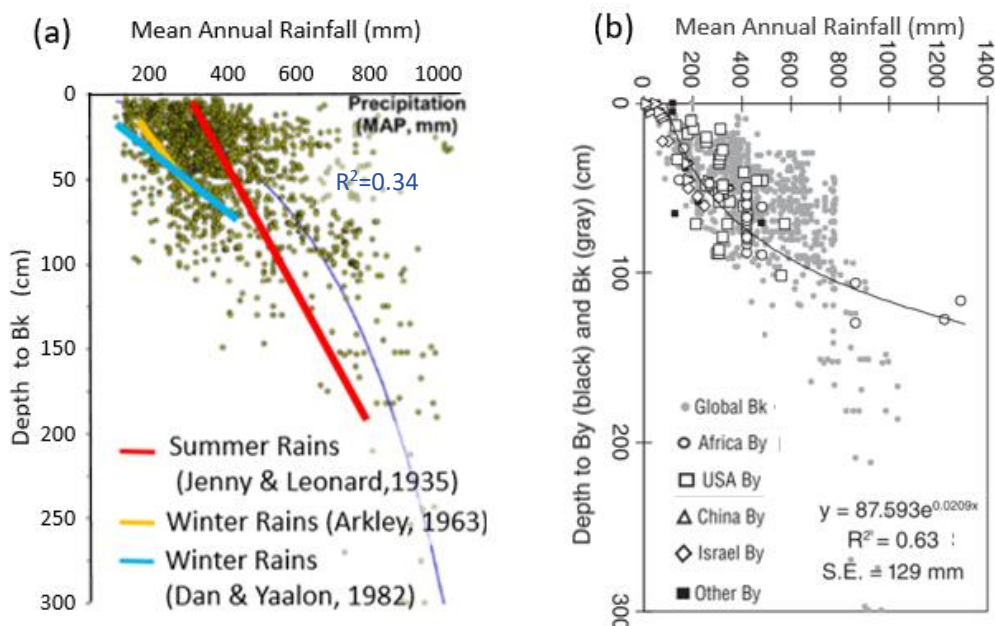


Figure 2
(a) Global data of 1542 depths to carbonate horizons and mean annual rainfall (modified after Zamanian *et al.*, 2016). Schematic lines of linear correlations derived from studies of 3 regions, are illustrated. Each associated with different rainfall distribution properties.
(b) Global data for 807 depths to Bk and By with correlation of depth to By and mean annual rainfall (after Retallack, 2010)

Arkley (1963) suspected that the intra-annual distribution of the rainfall along with the evaporation regime affect WDs, and therefore depths to Bk horizons in areas with winter rainfall are different comparing areas with summer rainfall. However, these differences were never quantified and the effects of individual climate properties on the trends or on individual depths to Bk horizons were never examined.

Arkley (1963) provided a modeling framework to calculate long-term WDs from data series of rainfall and evaporation. He verified his results by deriving reasonable soil ages. He also found that the "*mean depth of water penetration*" calculated for the sites in his study, indicate the depth to Bk horizons. It seems that the next step should have been to find out if this indicator can be applied in other sites and climates as a WD proxy for depth to Bk, but no such attempts were made.

Following studies improved our ability to reconstruct the formation of calcic horizons by adding chemical considerations to the existing models that considered only water balance. These studies simulated the long-term distribution of CaCO_3 along the soil profile in order to reconstruct CaCO_3 profiles in Holocene and late Pleistocene soils (Marion *et al.*, 1985; Mayer *et al.*, 1985; Mayer, 1986; McFadden, and Tinsley, 1985; Mayer, *et al.*, 1988). Pleistocene simulations were based on weather scenarios for past climate given from various paleo-climatic indicators. These models were validated using Holocene soil profiles and then were used to learn on plaeoclimatic conditions that led to the formation of late Pleistocene soils (Mayer, *et al.*, 1988). (e.g. Breecker *et al.*, 2009; Hirmas, 2008; Meyer *et al.*, 2014).

As mentioned above, past climate scenarios are given by a variety of paleo-research disciplines. In some cases, shifts in the mean annuals can be approximated, in other cases, the scenarios are restricted to obscure descriptions of wetter/dryer and warmer/colder than today. It's hard to say if wetter conditions or higher MAR, are the result of higher frequencies or intensities of rainfall events. Wetter conditions recorded in speleothems or lake sediments, could also be a result of shorter dry periods between rainfall events with the same MAR. It is unknown how changes in each of these climate properties affect these archives. In the past decade, these questions were raised also by researchers who are interested in the effect of future climate change scenarios on soil water that in turn

effect vegetation, soil salinity and flooding potential (e.g- Knapp *et al.*, 2008, 2015; Dunkerley, 2012).

Hydrological processes of the vadose zone are well understood in short term scenarios and WD resulted from a single rainfall event can be accurately estimated. For long term distribution of WDs, a modelling framework is required to track changes in soil water conditions, and to produce variant and realistic weather scenarios. The next section reviews soil water distribution processes in order to define WDs. In section 1.3 I will discuss models for long-term simulations of WDs, including soil water processes and long-term weather.

1.2 Climate control on water wetting depth in soil

Theoretically, a single rainfall event results in a final depth to which water has infiltrated and redistributed (WD). In reality, water distribution is a dynamic process that never stops. The soil water distribution does, however, slow down dramatically at dynamic steady states of the forces that control water movement and allow approximation of end points for soil wetting and drying events (Assouline and Or, 2014). WDs are the maximal depths where water flow reached at that end point. This dynamic nature of soil water distribution is controlled mostly by suction gradients in the soil that work to equalize soil pressures. Any change in water content would change the pressure field in the soil in 3D. It is responsive to continuous contributions and removal of water from the atmosphere through infiltration and evapotranspiration – both affect shallow layers first, and then proceed downward. This is why models of water flow in soils often describe this two processes in the 1D, in terms of: 'wetting front' and 'drying front' of high and low water contents respectively, that are more or less parallel to the surface – proceeding downward until either gravity, transpiration or evaporation cannot overcome soil suction. These semi-steady states are achieved in repeatable hydration states often referred to as field capacity (FC), wilting point (WP) and residual water content (θ_r) respectively. The water contents in these hydration states are mainly factors of the pore sizes, and are estimated by soil texture using pedotransfer functions (e.g. Rosetta program in Schaap and Van Genuchten, 2001) or by deriving a soil retention curve for soil samples in the lab. The difference between FC and WP water contents states is often referred to as the water holding capacity (WHC) or the available water capacity (AWC) of the soil, describing the

total amount of water a soil layer can hold in semi-steady state conditions. In some cases, θ_r could be appropriate as the minimal water content for WHC range.

A conceptual way to describe WD is that it represent the depth of the wetting front when it stopped, controlled by the amount of water income, the amount of water already held by the soil, and the soils' WHC (related to the soil texture). In reality, as weather continues its contribution to changes in soil pressure gradients, processes of wetting and drying may interact and steady states are not always achieved before another soil wetting occurs.

For each rainfall event, the soil's pre-existing water content would affect the WD, because each soil layer can hold limited water content of up to FC against gravitational flow. Therefore, tracking changes in water content through the soil profile is important for estimating the next WD. This is important in dry periods as well because, between rainfall events, evapotranspiration remove soil water from the shallow layers of the soil, re-establishing its capacity to hold more water and contributes to shallower WDs in the following rain. Therefore, in addition to the rainfall depth, WDs are sensitive to the distribution of rainfall events, seasonality and evapotranspiration regime (Knapp *et al.*, 2015).

The evapotranspiration is a complex process. The rate of soil drying changes as a function of the water content in the soil and the energetic demand from the atmosphere. While the weather forces a potential rate of evapotranspiration (PET), as soil dries, matric forces increase, and the actual evapotranspiration rate (AET) changes with the soils water content (Thornthwaite, 1948). Furthermore, because the evaporation is limited by the connectivity of water in the soil matrix, as the soil dries from the surface, downward, most of the water are removed by transpiration, and its potential rate is limited by the vegetation in the field. In agricultural research, estimates of the overall effect of vegetation on rates of transpiration is incorporated in a variable called Kc which can be either calibrated for, or taken as estimated value according to the type of vegetation this is usually an averaged effect because it changes in different stages of plant growth and by seasonality.

Because of the complexity of this process, studies of soil water dynamics usually combine modelling and monitoring practices. Measuring WDs in lab experiments or in the field can be done for a single test or rainfall event by detecting a clear transition from high to

low water contents. It is impossible to directly measure or monitor long term (time scale of 1-10k years) WDs and this is why not much discussion can be found about WDs in the literature – although its importance is obvious (e.g. Knapp *et al.*, 2015).

1.3 Models of water balance in soil

1.3.1 Water Distribution in soil

The dynamic nature of soil water described in the previous section implies the necessity of incorporating modelling tools to track and simulate soil water distributions. Soil water modelling is divided between two main approaches. One is physically based on numerical solutions of mass and energy balance equations (Richards, 1931), and the other is conceptual, based on simplifications of water flow and soil hydraulic properties, such as the compartment model, first presented by Arkley (1963).

Both approaches are not very difficult to implement. Physically based models have the advantage of being more accurate in the description of the actual processes; this is achieved in part by considering many soil parameters that control the water distribution in the soil. Yet, in long-term simulations, this accuracy may not be so useful because soils, soils' surfaces, and vegetation undergo many changes that affect soil water distributions and cannot be encompass in the modelling procedure. Instead, the compartment model, with its simplified approach and shorter computation time, has been proven to produce valid results in long-term studies that dealt with the formation of Bk horizons (McFadden, 1982; Marion *et al.*, 1985; Mayer *et al.*, 1985; McFadden and Tinsley, 1985; Mayer, 1986; Mayer *et al.*, 1988; Hirmas, 2008; Marion *et al.*, 2008). In addition, Arkley (1963) specifically designed his compartment model to track WDs and calculate the distribution of annual water fluxes in the soil profile. In physically based models, WDs has to be artificially defined and introduced into the model.

The greatest advantage of the physical models over the compartment models is that the evaporation process is much more accurate. While Arkley (1963) simply remove all PET from the soil column in a top-down direction, the physical models apply energy and mass balance at each point of the simulated soil profile to move water upward, encompassing the effects of momentary and local differences in suction gradients. Although this is a very attractive property, there is a significant trade-off.

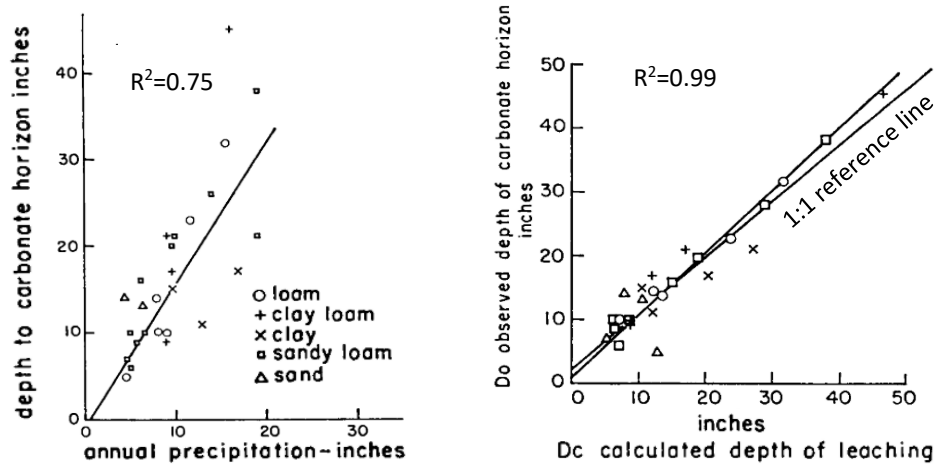
Soils with different hydraulic properties would distribute the same amount of water into different WDs (when given in length units of soil depths). In the compartment models, this is simplified by the WHC concept. Arkley's (1963) design of the compartment model calculates the soil depths of water distribution in WHC units and therefore WDs in soils with different WHCs can be compared (Figure 3) – this cannot be done in the physically based models. In addition, Arkley's (1963) model results may be applied to any soil if its WHC can be estimated – with no need of additional simulations. This is important, especially if one wants to develop a regional model (Marion and Schlesinger, 1994). In fact, if the global depths to Bk in Figure 2 would have been given in WHC units it might have reduced some of the scatter and effects of climate variability would be represented better.

Marion *et al.* (1985) improved upon Arkley's (1963) evaporation, adding a calculation of AET that considers the effect of soil water content on PET, and maintaining its ability to produce results in WHC units. This ability depends on the simplifications described earlier for the wetting and drying procedure. It is preserved as long as compartment are filled or dried to their limits of the WHC range, before the process proceeds downward to the adjacent compartment. Marion *et al.* (1985) used his model to simulate CaCO_3 deposition in four soil sites within Arkley's (1963) study area. They validated their model by reproducing the slope of Arkley's (1963) measured correlation of depths to Bk horizons with MAR (Figure 3.a). Others also adopted Marion *et al.*'s (1985) water distribution procedure with no changes to the AET sub-procedure (Hirmas, 2008; Marion *et al.*, 2008) and reported valid results. However, the studies mentioned above did not calculate WDs, but used the modified version of Arkley's (1963) model to simulate salts movement, adding chemical procedures that made their results soil specific.

Other compartment models (McFadden, 1982; Mayer *et al.*, 1985; McFadden and Tinsley, 1985; Mayer, 1986; Mayer *et al.*, 1988), used a different modification to the evaporation procedure including a gradient reduction of water content from the compartments with depth (Papadakis, 1965). Their water distribution procedure is more realistic however, its simulations using WHC units will not be consistent for different soils.

None of the previous compartment model studies used field measurements of soil water as inputs. Instead, they rely on estimates of WHC according to soil textures, and assessed the model's validity according to synthetic vs. observed Bk soil horizons.

It is also important to mention that all previous studies were deliberately focused on levelled surfaced sites, where runoff can be neglected. Therefore, their simulations assume all rainfall infiltrates the soil.



a) Correlation of observed depths to Bk with MAR – given in inches of soil depth

b) Observed depths to Bk (D_0) vs. calculated WD indicator (D_c) - given in inches of soils' water holding capacities

Figure 3 correlations from Arkley (1963): scatter of results in (a) demonstrate effect of diverse soils. In (b), Arkley (1963) use units of soil water holding to compare model results with the observations of depths to Bk given in (a), achieving nearly 1:1 relationship and high correlation.

1.3.2 Rainfall Generator

The long-term soil water modelling requires an input of climate data set of thousands to ten thousand years. These data must represent longer time series than measured, but with similar statistical properties to the climate under study.

Marion *et al.*, (2008) noted the significance of extreme events on long term salts translocations in the soil profile, and criticized others for using deterministic rainfall models, in which the same average rainfall pattern is repeated year-after-year. These models frequently use monthly time steps, that are not event based, and are likely to obscure both the effects of extreme rainfall events within years and extreme rainfall years within centuries (Marion and Schlesinger, 1994). Marion and Schlesinger, (1994) advocate for using a daily time scale to allow simulations to be similar to the actual climate variability. Few studies (Marion *et al.*, 1985; Marion *et al.*, 2008) based their rainfall generator on the interarrival time and daily precipitation based on cumulative probability distributions for each site and season. Marion *et al.*, (2008) comment that his model may be reasonably

valid for short-term simulations (a few hundred years), but less accurate for long-term simulations (>1000 years), probably because the maximum rainfall was limited by a 25 years record, which affected the representativity of extreme events in their simulations. Rainfall models often fit data with distribution functions to produce results that could have been in the record had it been long enough. In addition, a stochastic component must be used for random choice of values from distribution of rainfall data to create variability. Too many parameters controlling the generator will reduce the variability, and therefore it's best to achieve realistic behavior of the data with as little properties as possible. On a daily time scale, at a site, simple rainfall models are based on either Markov chains (Richardson, 1981) or empirical distributions of wet/dry spells (Semenov and Brooks, 1999). Rain depth is then determined from frequency distributions that represent natural rainfall data sets. Rain depth distributions are generally skewed to the right, thus gamma or exponential distributions often best simulate these distributions (Dunn, 2004).

1.3.3 PET Generator

For simulations of long term evaporation, Marion *et al.* (1985), and Marion and Schlesinger, (1994) used tabular data of PET measurements done with a standard pan, where it was available. Otherwise, monthly temperatures were converted to PET using Thornthwaite equation (Thornthwaite, 1948). These empirical distributions of the data do not allow much variability. In addition, PET cannot be measured with pans in rain days and therefore the record might bias the mean daily PET. Hirmas (2008) used a slightly different technic in which temperatures followed a stochastic sine function fitted to a set of daily temperature data for one year.

In both examples, some of the PET simulations have been predicted using temperature measurements. Records are much longer for temperature data than PET measurements, however, temperature is only one of three major factors that affect PET. The relative humidity and radiation income have significant effects on the overall energy input into evaporating soil water to the atmosphere (Howell and Evett, 2004). Cloud cover and winds alter the effect that the temperatures have on PET. It has been agreed that the most reliable daily PET estimation comes from Penman- Monteith calculation (Howell and Evett, 2004).

The Penman - Monteith calculation is very accurate but its data set is limited. Tsakiris, 1984 simulated daily PET in four different climates with relatively short data series, and retrieved satisfying monthly means and variances. His model encompasses some effects of cloud cover and winds that sometimes follow or precede rain events. They drew separate distributions for wet or dry days, taking the condition of previous day into account as well. He also added the effects of the monthly mean and variance into account.

To summarize the background chapter, there is a clear relationship between MAR and depths to Bk/By horizons that is manifested in soil record. This can be a powerful tool for paleo-climate reconstructions. However, variability of the correlations derived in different climates suggest influence of additional climate properties on the record that have not been quantified. Estimates of these effects would help to establish, validate or choose between suggested climate scenarios.

Arkley (1963) created a model that calculates long term WDs and found a correlation to Bk horizons. That provided a theoretical explanation for how MAR is correlated to the depth of soil horizons (Birkland, 1984). This framework was validated by many following studies of CaCO_3 and CaSO_4 deposition; therefore, depths to Bk and By horizons are markers of the long-term WDs. However, mean WD (as suggested by Arkley, 1963) or any other WD property was never verified as an indicator of depths to Bk/By. Processes of climate and soil water distributions are well understood in short timescales, and can be simulate better than simulating salts dissolution, translocation and precipitation that depend on more variables. However, WDs are rarely discussed in short or long-term scales. Calls are being made today to quantify relationship between climate properties such as rainfall distribution and temperatures effects on soil water distribution, because this is missing link in the effects of future climate scenarios on vegetation, soil salinity, recharge, floods, etc.

Although measurements of soil water contents can be done fairly easily, there is great uncertainty in their analysis because of soil and climate variabilities. Although compartment models simulating salts movements seem to have been validated, they did not base their models on calibrated parameters regarding soil water, and did not show short term water movement predictions to fit observations.

2 Goals

The main goal of the research is to quantify the influence of climate on the long term WD frequency distribution in loessial soils that in turn control salt accumulations in soil horizons.

Specifically, the objectives of the study are:

1. Develop a simplified soil water balance compartment model to simulate long term frequency distribution of wetting depths in a loessial soil.
2. Develop a point stochastic weather generator of relevant climatic factors to represent the climate of the northern Negev of Israel, based on meteorological data.
3. Quantify the controlling climatic factors for the development of long term frequency distribution of wetting depths through sensitivity analysis.
4. Provide insights for paleo climate reconstruction and analysis from depths to Bk records.

Hypothesis: statistical indexes of soil water distributions can be correlated with depths of salt accumulations in soils, and can be used as a proxy to learn on the climatic control on these soil horizons.

3 Study site

The northern and central Negev desert in Israel are covered by extensive loess and loessial soils with relatively similar textures (Crouvi, 2008). MAR varies dramatically from north (350 mm) to south (100 mm) and therefore it is a suitable area to study the effect of climate properties on salt accumulation in soil. The region is relatively homogeneous with respect synoptic conditions, rainfall seasonality (only winter rains) temperatures and evaporation patterns.

The soils in the area with >200-250 mm are characterized by calcic horizons, whereas the area with 80-(200-250) mm exhibit both calcic and gypsic horizons, the latter are more pronounced in the southern part of this region (Fig. 4). More to the south, where average rainfall is <80 mm, only gypsic horizons are evident. The loess encompasses several buried soils that represent the climatic conditions during the time of their formation within the late Pleistocene. There is a consensus that the region was wetter during the late Pleistocene comparing the Holocene; however, it is debatable whether it has been influenced by colder conditions resulting in lower PET, with no increases in rainfall depths (Bar-Matthews *et al.*, 2003), or by higher frequencies and intensities of cyclonic fronts from the Mediterranean Sea which are the main contributor to rainfall regime in the area (Enzel *et al.*, 2008; Amit *et al.*, 2010).

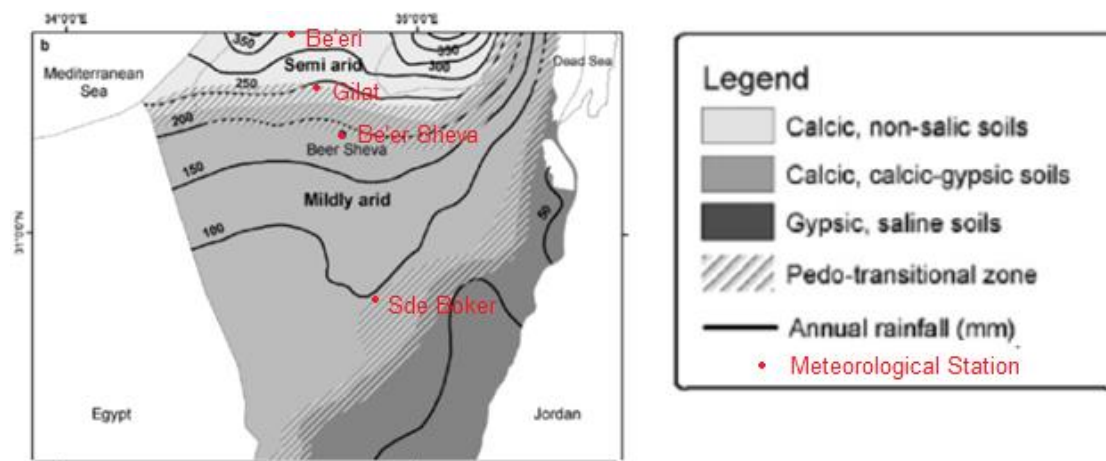


Figure 4 Map of the Negev desert with spans of salts horizons and MAR isopachs. Schematic locations of 4 meteorological stations that were included in the climate analysis for the research are marked.

3.1 Current climate in the northern Negev

The northern Negev is a transition zone between the wetter, Mediterranean climate region of central and northern Israel (300–800 mm yr⁻¹) and the more arid central and southern Negev. MAR decreases from 350 mm in the north-most part of the region to about 80 mm at the Negev highlands that divide the Negev region to its semi-arid northern part and the hyperarid south. Rainfall is directly related to Mediterranean moisture influx from the west and southwest (Enzel *et al.*, 2008).

According to data from 4 meteorological stations in the area, the regional trend of MAR is mostly a consequence of the mean daily depths reduced to the south. The number of rainfall days, mean number of events per season and their durations are relatively similar through most of the northern Negev, and drop in the central part. These trends are a geographical consequence of the distance from the Mediterranean (Table 1).

The local variance of the MAR is controlled by the number of rainfall events, durations and the daily depths (e.g. Gilat wet and dry years in Table 1).

Table 1 Mean Rainfall properties of data sets from 4 meteorological stations in the northern (from north to south: Beeri, Gilat, BeerSheva) and central Negev (Sde Boker). Mean properties of relatively dry and wet years for the Gilat meteorological station are also given at the bottom. Rainfall data was received from IMS.

site	Mean annual rainfall (mm)	Mean daily depth (mm)	Number of Wet Days per year	Number of events per year*	Mean events depths (mm)	Mean events duration s (days)	Station ID	Period
Be'eri	352.0	8.9	39.4	19.8	18.0	2.0	144249	[1950,2018]
Gilat	237.6	6.5	36.6	19.0	12.8	1.9	251349	[1953,1996]
Be'er Sheva	191.6	4.8	39.6	20.5	9.3	1.9	251690	[1957,2009]
Sde Boker	89.7	3.4	26.6	15.8	5.9	1.7	253000	[1952,2018]
Gilat dry**	133.6	5.3	26.8	15.1	9.3	1.8	251349	[1953,1996]
Gilat wet***	359	7.8	46.9	21.1	17.6	2.25	251349	[1953,1996]

* one day day separation criteria for rainfall events

**properties of dry years in Gilat station when annual rainfall < MAR - 30%

***properties of dry years in Gilat station when annual rainfall > MAR + 30%

Evaporation rates are highest in the summer season and are higher at the southern part of the region, however, at winter, these averages converge and there is no clear spatial trend. In any case, the spatial differences between the mean values of evaporation are not much different than the variance of each station.

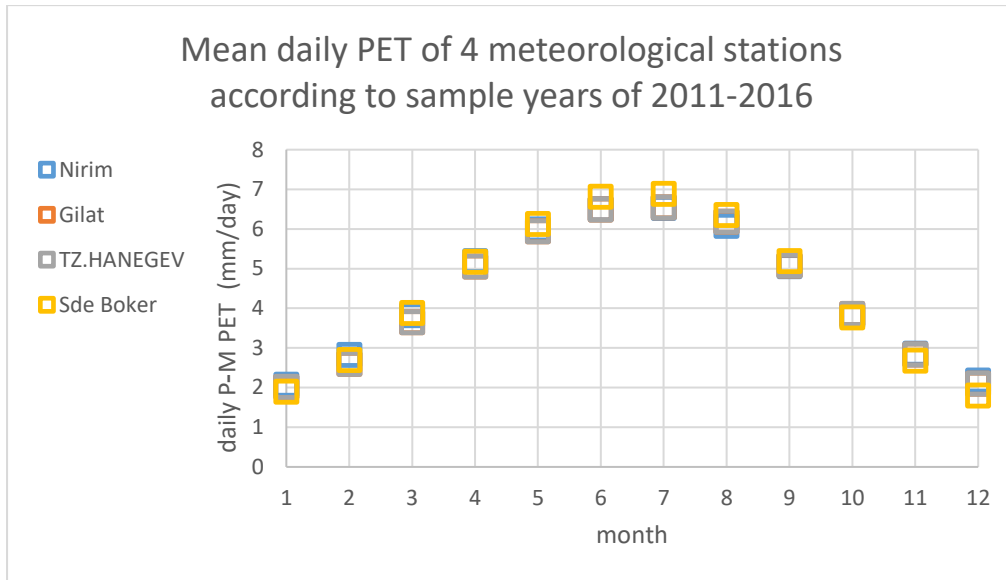


Figure 5 Intra-annual variance of the mean daily evaporation in 4 meteorological stations in the Negev. Locations from north to south: Nirim-Gilat-TZ.Hanegev-Sde Boker

3.2 Monitoring site

Gilat agricultural research institute is situated in the northern Negev (Figure 4). In Gilat, soil water content monitoring station was installed in an abandoned farming land. Data from the monitoring station was taken for calibration and validation of the model (see below). The soil surface is covered mostly with annual vegetation. Few eucalyptus trees which are foreign to this area (not older than 150 years) are located 50-100 m away from the monitoring station. Agricultural activity in this field hasn't been active for at list 30 years, however, in the past, it was farmed with various crops, and therefore the top soil was interfered and the irrigation has influenced salts translocations for at least 50 years of farming. Clear A and B horizons were defined in the soil profile in Gilat, overlying some buried soil horizons in depths exceeding 50 cm. The B horizon was defined at depth range of 30-50 cm (Appendix II). Within this depth range some secondary carbonates were found, however, it was not apparent enough in the section to be classified as a Bk horizon

(Figure 6.a). Within a distance of about 1 km from the monitoring station, un-interfered soil profile near Mishmar-HaNegev was described in an unpublished report by O. Crouvi (Figure 6.b). This soil profile displays a distinct Bk horizon at 30-50 cm, overlying some buried Bk horizons. The carbonate distribution in Mishmar-HaNegev profile is considered here to represent the natural carbonate distribution that should exist in the Gilat profile. A comparison between soil properties of the Gilat and Mishmar-HaNegev profiles was done and displayed in the results section.

In the central Negev, where MAR is 80-100 mm/year, another monitoring station was installed in Sde Boker – Institute for desert studies (Appendix III). The data from this monitoring station were received later in the study and were used for comparative of parametrization only.

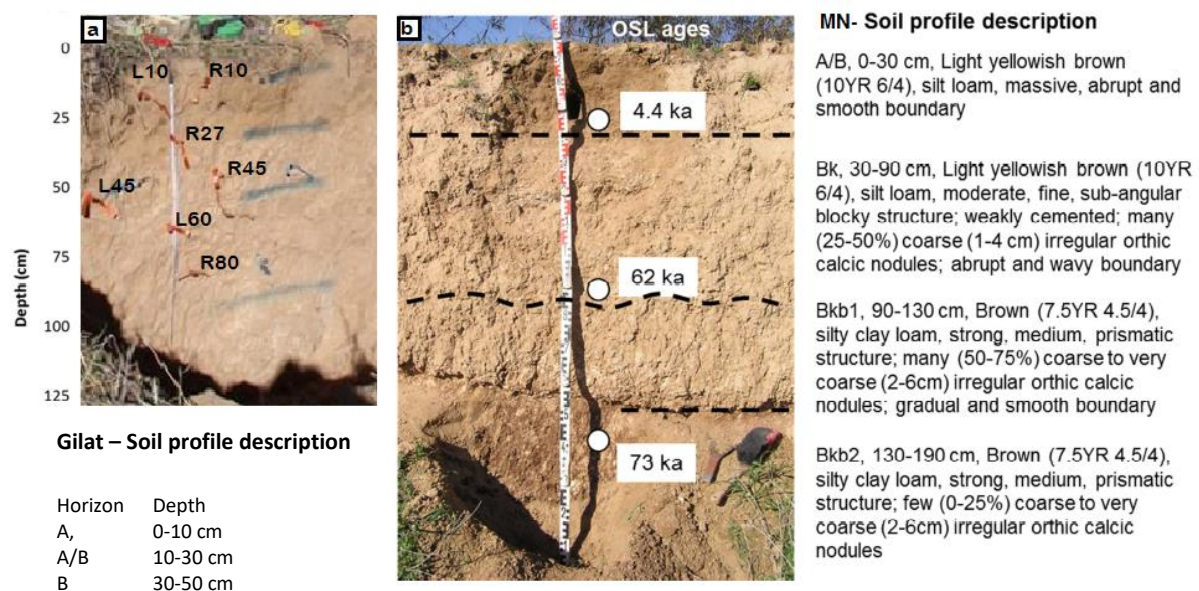


Figure 6 soil profiles with Bk horizons in the study site: (a) from Gilat monitoring station, with prescribed sensors locations and grey marker for division between soil horizons; and (b) Mishmar-HaNegev (MN) located within 2 km from the site in Gilat, with OSL ages of secondary carbonate from an un-published data of Dr. Onn Crouvi (GSI).

4 Materials and methods

This study included five main steps:

1. Building models and calibrating them to represent soil water dynamics and weather in Gilat (analysis of soil samples and monitoring data of Gilat and Sde Boker sites are described in Appendix IV).
2. Adjusting the rainfall generator parameters to represent other sites in the Negev. Soil and evaporation parameters were assumed similar for all simulations of the Negev sites.
3. Calculating long term WD and flux distributions using measured and synthetic data of 3-4 meteorological stations throughout the northern Negev.
4. Finding properties of these distributions that can be associated with depths to Bk and By horizons, and reinforcing them as proxies for these soil horizons by comparison of their trends with MAR and the reported trend for this region.
5. Testing local and global sensitivities of the proxies to various climate scenarios by calculating them with synthetic weather created by different sets of parameters.

This chapter is divided into sections explaining each model. First I explain the compartment model and its products (steps 1,3 and 4) in section 4.1; Then, in section 4.2, I explain how the rainfall and PET generator works (steps 1,2), finally, in section 4.3 a general overview is given for the sensitivity analysis done here (step 5).

4.1 The compartment model

The compartment model simulates the vertical distribution of soil water as a response to daily rainfall and PET inputs. The daily procedure is taken in three steps. 1) At the beginning of each day, soil water content in the top 20 compartments (0-1m) of the soil is calculated to determine the amount of AET that will be taken out of the soil column. 2) The entire daily rainfall infiltrate into the soil, assuming no runoff and only gravitational flow, and distributed between the compartments, 3) the daily AET is taken out of the compartments.

4.1.1 Soil space in the model

The soil space is simulated as a stack of 80 compartments, each representing a 5 cm soil layer with a fixed water holding capacity (WHC) between θ_r and FC water contents (Figure

7). The soil column modeled in this study is 4m thick. The water content limits were assigned according to θ_r and FC water contents of the soil in Gilat (see section 5.1.4)

4.1.2 Infiltration and downward flow

All daily rainfall is assumed to infiltrate into the soil's uppermost compartment. The compartment must be filled to its FC water content before water may proceed downward to the adjacent compartment. The flow stops when all of the daily rainfall depth was distributed. The depth of the lowermost compartment that received water increase was logged as the daily WD. Any excess rainfall depth left after all compartments were filled was assumed to leach out of the soil to groundwater. In this case the daily WD is at compartment 80, representing 395-400 cm depth.

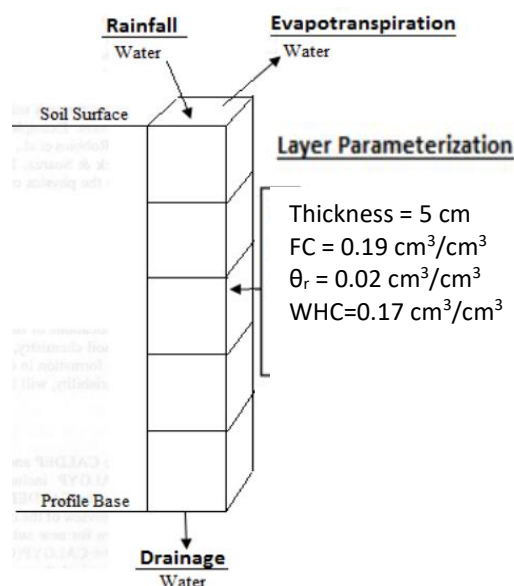


Figure 7
The compartment model scheme
(modified after Marion et al,
1985).

Daily WDs, downward water flux from each compartment and the total number of days at which each compartment was full to its upper limit, were logged in variables named WD, WaterFluxOut and WetZone accordingly. These variables were later used to describe and analyze the long term soil water distribution in relation with climate properties (section 5.1.5).

4.1.3 Evaporation procedure and soil water content test for AET

Similar to the downward flow of infiltrating daily rain, the daily AET is taken out from the soil profile top-down and evaporates instantly (assuming no upward flow). Water is taken out first from the uppermost compartment. A compartment must be emptied to its lower WHC limit (θ_r ; water content), before any water is taken out from the next compartment.

The procedure stops when all daily AET was taken out. The AET is calculated from the daily PET using the calibrated crop coefficient (K_c) and the amount of total water content in the profile at the beginning of each day according to eq. 1 (Marion et al., 1985).

Marion et al. (1985) simulated only 1-1.5 m of soil profile, and therefore tested the total water content of their profile to force its effect on the AET. This effect decreases with

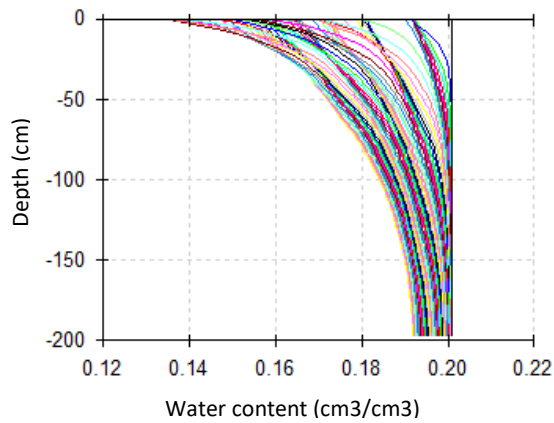


Figure 8 HYDRUS 1D simulation of water content profiles over the rainfall season of 2016/17 in Gilat – most changes in water content are restricted to the first 1m of the soil profile

depth. Here I simulate a 4m deep profile to include deep WDs and therefore the total water content at the topmost 1 m of the soil is considered. I justify this choice with Hydrus 1D simulations (physically based model) that suggests changes in water content are mostly restricted to these depths in Gilat (Figure 8). Further consultation with Prof. Shmuel Assouline (Volkani Institute), re-enforced this assumption.

eq.1:

$$\begin{aligned}
 (1) \quad AET &= K_c * \begin{cases} PET & \text{if } TotalMoisture > WHCindex * TotalWHC \\ \frac{TotalMoisture}{TotalWHC} * PET & \text{if } TotalMoisture \leq WHCindex * TotalWHC \end{cases} \\
 (2) \quad TotalWHC &= \sum_0^{T.M.Depth} WHC, \quad T.M.Depth = 100cm \\
 (3) \quad WHC &= FC - \theta_r
 \end{aligned}$$

WHC here is the water holding capacity of each compartment and is given in 1D water content units (cm/5cm), as are the field capacity (FC) and the residual water content (θ_r). $T.M.Depth$ is the maximal effective depth for ET processes, prescribed here at 100cm – or at compartment number 20. $TotalWHC$ is the sum amounts of WHC of the compartments within depths of 0– $T.M.Depth$ (cm). $TotalMoisture$, is the sum amounts of existing water contents within depths of 0– $T.M.Depth$ (cm). $WHCindex=0.546$ (Marion et al., 1985) is the point in WHC range, at which AET turns from being energy limited (i.e., controlled by the atmospheric demand, $AET=PET$), to soil moisture limited. This value was taken from

Marion et al. (1985) as there was no other source available. K_c is the crop coefficient that limits PET according to variable vegetation conditions. This variable was calibrated to include conditions in Gilat and assumed to be similar for other sites in the Negev.

4.1.4 Model parametrization

Materials were collected from soil samples, reported soil properties and time-series of soil water contents from monitoring stations. The limits of the soil's WHC were deduced from analysis of soil samples taken from Gilat and Sde Boker sites, and water content measurements from Gilat soil monitoring station. It was reinforced by calibrating an optimal FC which is consistent with all other estimations. The crop coefficient was calibrated using data series of weather and soil water contents from the Gilat monitoring station. Details of the extraction of soil and water content data, as well as the calibration procedure are summarized in Appendix IV.

4.1.5 Proxies for depths to Bk and By horizons

In search of water distribution properties that could be associated with the depths to Bk horizons, I first simulated water distributions of three sites with known depths to Bk horizons and the longest measured times series of daily rainfall. Then, for each site, I calculated percentiles, means, and vertical distributions of the three soil water loggers: WD, WaterFluxOut and WetZone variables (discussed previously in 4.1.2). Few of these properties were found to correlate with known depths to Bk horizons at all three sites.

The simulations were conducted using the compartment model with inputs of: the optimal set of parameters that was found for Gilat site with the calibration procedure (see in 5.2): $K_c=0.6$, $FC=0.19 \text{ cm}^3/\text{cm}^3$, $\theta_r=0.02 \text{ cm}^3/\text{cm}^3$; rainfall data-series of Be'eri, Gilat and Sde Boker meteorological stations (retrieved from IMS website); and synthetic daily PET series. Because of insufficient evapotranspiration data, the simulations were conducted with synthetic PET created with the PET generator (section 5.2.2).

Reported depths of the top of Bk soil horizons are:

1. Be'eri: depth to Bk reported at 50cm (Eisenberg, 1980).
2. Gilat: depth to Bk is 25cm according to Dan and Yaalon (1982) and 30cm according to soil profile of the monitoring station and an unpublished soil profile at Mishmar HaNegev – from Dr. Onn Crouvi.

3. Sde Boker: depth to Bk is about 15 cm according to the soil profile in Sde Boker soil monitoring site, and according to Dan and Yaalon (1982).

Vertical profiles of three soil water loggers for all sites showed consistent associations between the depths to Bk horizons described above and depths of the following: the mean of the WD distribution (MeanWD), the 80th percentile WD (WDp80) and depth where WaterFluxOut is 30% of the total rainfall in the simulation (Index30).

Further simulations using long-term synthetic weather reinforced these as proxies for depths to Bk horizons. The synthetic weather data was generated to be of periods of 500-5,000 years by the weather generator (see section 4.21). The trends of the calculated proxies with MAR at each site were then compared with the reported trend of depths to Bk horizons for the region (taken from Dan and Yaalon, 1982).

As Bk horizons were associated with the distribution of all daily WD's, I examined if By horizon depths could be associated with the distribution of maximal seasonal WD (SWD) or with much smaller fluxes that percolate deeper into the soil. SWDs were taken out of the long term WD distributions. The mean and 80th percentile SWD (MeanSWD and SWDp80), and the depth where WaterFluxOut logged only 3% (Index3) of the total rainfall for all 4 sites. MeanSWD, SWDp80 and Index3 were plotted against MAR for each site and compared with the trend of gypsic horizons in Dan and Yaalon (1982).

Depths in the WD distribution were taken as the mid-depth of each compartment. Depths of Index30 and Index3 were calculated by linear interpolation of two adjacent compartments of WaterFluxOut that contained relative fluxes of larger and smaller than 30% and 3% of the total rainfall respectively.

The final step was to calculate proxies for a range of weather properties and to quantify effects of different properties on the depth of the proxy. This was done by running the compartment model with the synthetic weather with various properties. The next section, explains how the synthetic data series were generated.

4.2 The weather generator

A weather generator was first built to simulate weather with similar statistical properties as in Gilat. It is composed of two components: rainfall and PET generators - described in 4.2.1 and 4.2.2, respectively. The rainfall generator was later on adjusted to simulate rain

in Be'eri, Beer Sheva and Sde Boker as well. It was built to simulate other weather scenarios as well by four parameters which control mean properties of: daily rainfall (A and B), number of events per year (Fd) and events durations (Fw). The PET generator was built to simulate daily evaporation in Gilat, and applied the same to all sites. However different evaporation regimes are generated for different intra-annual rainfall distributions. To simulate scenarios with higher and lower PET, or higher and lower Kc, I used a simple factor (F_{PET}) over the entire PET series.

A,B,Fd,Fw and F_{PET} are the five weather parameters that were used in the sensitivity analysis to simulate and quantify the control of weather properties on proxies for depths to Bk and By horizons.

The construction and validation of the rainfall and the PET generators required initial analysis of rainfall and PET properties. Wet and dry days were defined in order to separate probabilities for rainfall and PET conditions within rain events and within dry spells: Wet days are rainy days with rain depth ≥ 0.1 mm, and dry days are days with rain depth of 0-0.1 mm.

Initial distributions were derived from the following data-series from meteorological stations in Gilat:

1. **Daily rainfall data from Gilat (station 251350) for time period of 42 years (1953-1996) (IMS reports).** Based on these data I have derived the following distributions: (1) daily depths of rainfall (2) probability of wet day occurring after a dry day (PWAD) to describe a beginning of a rain event, and (3) probability of a wet day occurring after a wet day (PWAU) to describe the chance of an event to continue if it had started in previous day/days. PWAU and PWAD are empirical probabilities given for each day in a 365 days year. A Weibull function was fitted to the empirical distribution of the daily depths – with the scale parameter A, and the shape parameter B controlling the function. Gaussian functions were fitted to the empirical distributions of PWAD and PWAU – with Fd and Fw controlling the height of the Gaussians to simulate weather with higher/lower frequencies of events, and longer/shorter durations respectively.
2. **Rain and Penman-Monteith type PET data from Gilat (station 7580) for time period of 16 years (2002-2018) (Ministry of Agriculture reports).** Based on these data I

derived the following distributions: daily depths of PET at four types of days (WAW- wet after wet for days within rainfall events, WAD - wet after dry for the first day in rain events, DAW-dry after wet for the first day after a rain event, and DAD-dry after dry for days within dry spells) and for each month of the year.

4.2.1 The rainfall generator

The synthetic rainfall data were created in two steps. First, a day was determined as wet or dry by semi-random choice out of the PWAD distribution if the previous day was dry, or out of the PWA distribution if the previous day was wet. The first day of simulations was always assumed to succeed a dry day. Second, the daily depth was chosen from the daily depths probability distribution. The rainfall generator scheme is illustrated in Figure 9.

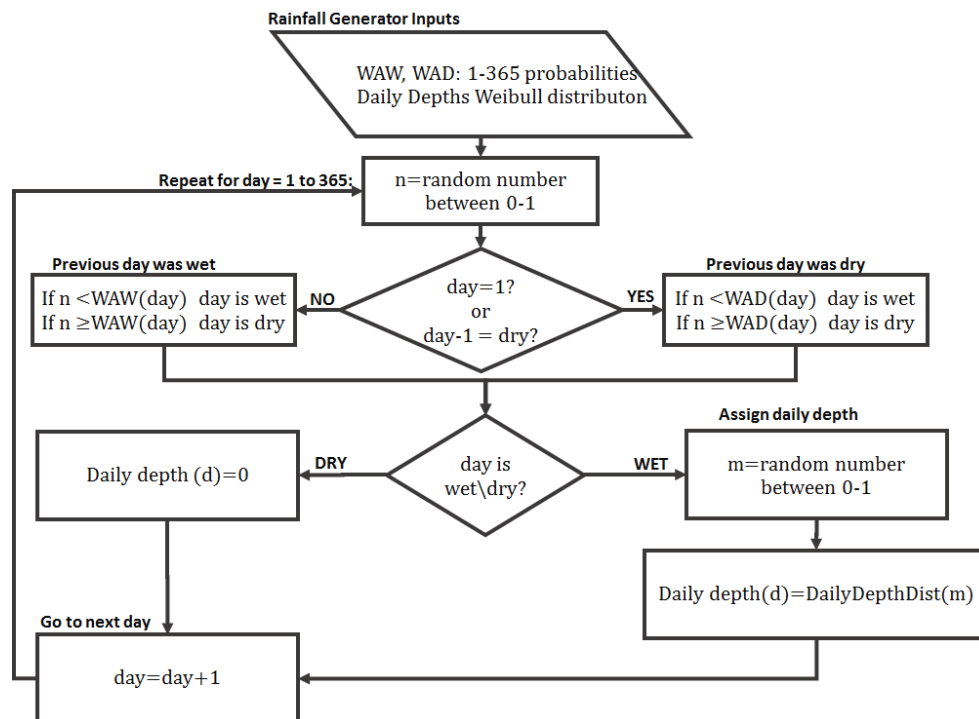


Figure 9 The rainfall generator scheme for 1 year of synthetic data generation. The year includes days numbered from 1 to 365, representing the hydrological year starting at sept-1st, and daily depths (0 for a dry day).

In both steps, a random number between 0-1 was ruffled from a normal distribution. It had to be lower than the given probability for a wet day in PWAD or PWA – otherwise it was determined dry. On the second step, a second random number was ruffled to choose depth of rainfall from the daily depths distribution.

This rainfall generator was created based on measured data from Gilat meteorological station. The empirical PWA and PWAD values were plotted as a function of the day in the year, then smoothened with a 15 days- running window, and then fitted with a Gaussian (Figure 10).

The two Gaussians control the frequency and durations of rainfall events, with PWAD representing the chance of a daily rainfall to occur after a dry day, and the PWA, representing the chance of a daily rainfall to occur after a wet day. Therefore, frequency and durations of events can be controlled by the heights of these two Gaussians. The Gaussians control the frequency and durations of rainfall events, with PWAD representing the chance of a daily rainfall to occur after a dry day, and the PWA, representing the chance of a daily rainfall to occur after a wet day. Therefore, frequency and durations of events can be controlled by the heights of these two Gaussians.

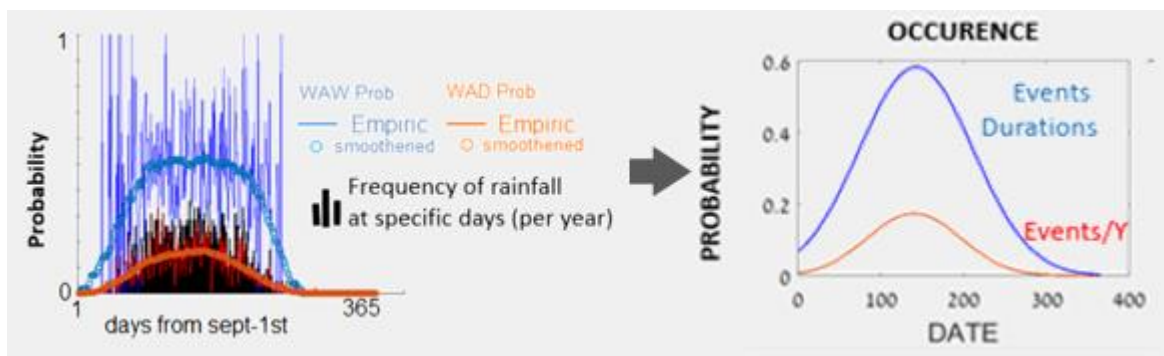


Figure 10 Schem for deriving gaussians from measured rainfall data for the probabilities of generating rain days (PWA and PWAD) with the rainfall generator in this study. On the left: empiric probabilities of WAW and WAD days. Smoothened by a 15 days running window. On the right: the fitted Gaussians specifying the control of PWA over events duration (blue) and the control of PWAD over Events/year (orange).

A Weibull function was fitted to distribution of daily depths in Gilat. I used the scale parameter (A) of the Weibull distribution to control the mean daily depth of the synthetic series. Changing the shape parameter (B) did not affect the goodness of the results in a definite way and therefore was fixed on the value retrieved for Gilat. The rainfall generator was validated by comparison of means and standard deviations of rainfall properties in the measured data and in 100 synthetic series generated the same parameters.

Simulating rainfall for sites in Be'eri, Beer Sheva and Sde Boker was done as following:

1. Sensitivity analysis was conducted on 3 parameters: the scale parameter of the daily depth Weibull distribution - A, a factor over the PWAD Gaussian – Fd, and a factor over the PWAW Gaussian-Fw. The parameter values were plotted against the resulted properties of the simulations' synthetic rainfall – the mean daily depth, mean number of events per year and the mean events duration respectively – from which functional relationships between parameter and mean property were created.
2. Table 1 summarizes mean properties of rainfall data of Be'eri, Be'er Sheva and Sde Boker. These were calculated from data-series reported from the meteorological stations at these sites (source – IMS; id number and periods in Table 1).
3. For every site, I used the functions from step 1 to get the appropriate set of parameter. Then, I compared statistics of rainfall properties derived from 100 simulations and the statistics of the measured rainfall series for each site (Appendix IV).

4.2.2 The PET generator

Following Tsakiris's (1988) PET generator, means, standard deviations, autoregressive coefficients and skewness of daily PET were derived for WAW, WAD, DAW and DAD types of days, in each month of the year, from the 16 years long time series of daily PETs in Gilat. The model is autoregressive and the daily PET was calculated based on all of the above and on the PET derived for the previous day. A normal random variant exist in the calculation for stochastic variation of the values. The method is explained thoroughly in Tsakiris (1988).

For validation I compared mean monthlies and standard deviation of the measured daily PET in Gilat with means and standard deviations of synthetic PETs. These were created using synthetic rainfall time series for Gilat to allow various distributions of WAW, WAD, DAW, DAD type of days.

A factor over the PET data series (F_{PET}) was installed to create climates with greater or lower evaporation rates.

4.3 Sensitivity analysis

The last step in this study was to quantify the effect of climate properties on long-term WDs and soil water distribution. I simulated various climate scenarios with the rainfall generator and calculated proxies for depths to Bk and By horizons using the compartment model.

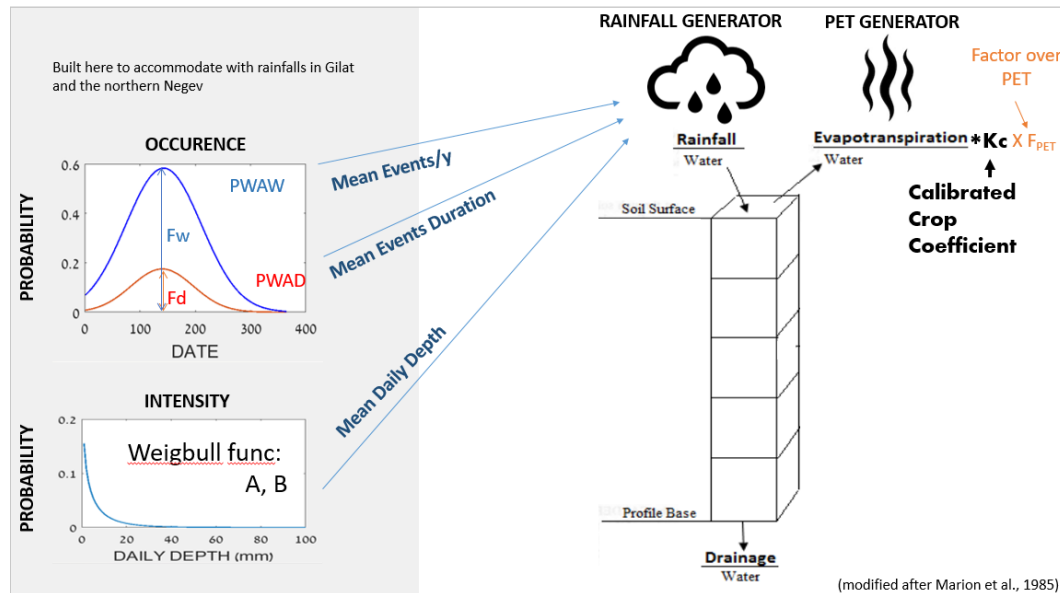


Figure 11 A scheme of the combined weather and soil models: Rainfall parameters- A , B , F_d , F_w control probabilities of rainfall occurrence and depths and therefore influence mean properties of the rainfall distribution. F_{PET} is a factor over the daily PET series. Results of the compartment model (i.e.-depths to Bk and By proxies) change with these 5 parameters

First, 5000 years of synthetic weather were created with the calibrated rainfall parameters for Be'eri, Gilat, Be'er-Sheva and Sde Boker. These were used as input data to the compartment model to calculate the reference proxies for the depths of Bk horizons. Local sensitivities were then quantified for 20% differences in all five weather parameters for each site on the depths to Bk horizons proxies comparing results with reference proxies. Maximal absolute differences of proxies' depths and mean weather parameters were illustrated to discuss ranks of effects of the various properties and parameters. Local effects of the rainfall parameters on the trends with MAR were also illustrated by calculating MeanWD with only one rainfall parameter change at a time. This approach allowed me to reveal trends for regions where the rainfall distribution vary by only one main property of mean daily depth (by 1mm interval changes in A par.), mean events per

year (EventsN – by 0.1 interval changes in Fd par) and mean events durations (EventsDurations – by 0.1 interval changes in Fw par.)

For the global sensitivity analysis, about 1500 data series of rainfall were created with various sets of parameters using the rainfall generator (Table 2). For each rainfall data series, an evaporation data series was created with the PET generator. These data sets were inserted into the compartment model for simulations of soil water distribution and produced results in the form of WD distributions, and depths of proxies for the top of Bk and By horizons. I ran each simulation three times with different evaporation factor for: $F_{PET}=0.5, 1, 1.5$ – Illustrating the effects of 50% increase or decrease in the mean PET within the rainfall season on various rainfall scenarios.

Table 2 Ranges of rainfall parameters included in the simulations for global analysis

Parameter	Range	Intervals	Affected prop.	Range of means for affected prop.
A	0.5-9.5	1	daily depth	0.7-11.6 mm
Fd	0.2-4	0.2	events per year	3.8-61.5 events/y
Fw	0.2-1.8	0.2	events duration	1.1-9.9 days/event

The results were limited to mean affected properties in Table 2 and by mean annual number of wet days of 100 days/year. This is according to statistics of mean annual wet days given in Morin *et al.* (2019) for hyper arid to dry subhumid regions. Results were also limited by MAR <900mmPa/year according to the expected range in global record of depths to Bk and By horizons.

These results were plotted against weather parameters and mean properties of the rainfall distribution: MAR, EventsN, DailyDepths, EventsDepth, EventsDurations, DrySpells and frequencies of extreme events to demonstrate controls of various properties on the depths and trends of Bk horizons with weather properties. In the result section I present some of the results that contribute insights for discussion. Global sensitivity of depths to By horizons is given in only one plot against MAR for demonstration.

5 Results

5.1 The compartment model

5.1.1 Soil Texture

The textures measured for the soil profiles in Gilat and Sde Boker are relatively uniform and similar. Description of the profiles is given in Appendixes II-III, description of the sampling and analyzing of the samples is given in Appendix IV.I. The soils' textures are classified as silt loam to loam, with higher silt component in Sde Boker profile (Figure 13). FC and θ_r were estimated using the Rosetta model (Schaap and Van Genuchten, 2001) and measured values of textural percentages and bulk density of soil samples (Table 3, 4).

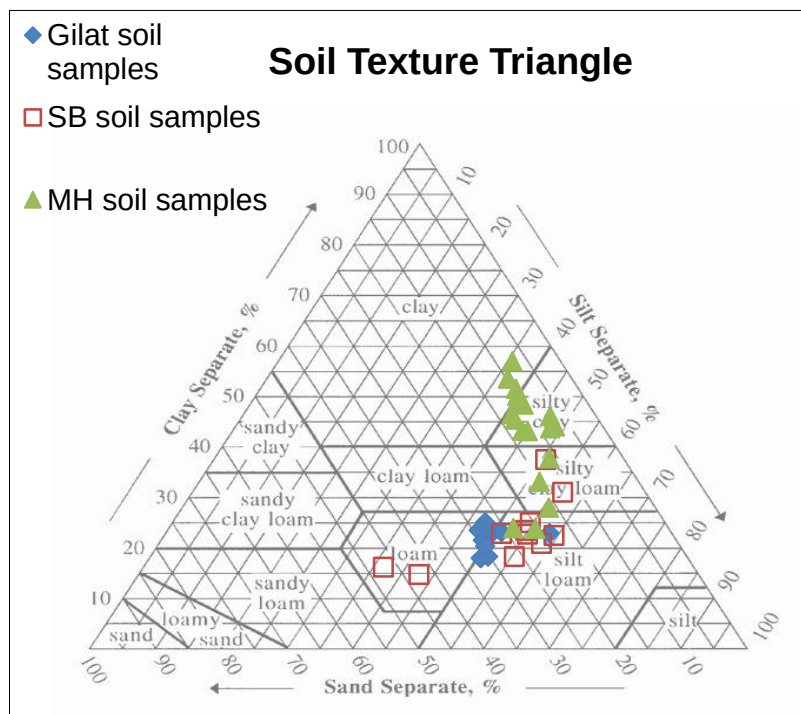


Figure 12 Soil textures of soil samples from Gilat, SdeBoker (SB) and Mishmar HaNegev (MN) profiles. MN profile data was taken from unpublished data of Dr. Onn Crouvi of the GSI. In Sde Boker most of the profile is classified as silt-loam apparat from 4 samples that represent negligent parts of the profile. Two were taken from the upper-most loamic 6 cm of the profile (samples: 2769, 2770 in Table 4); and the two other samples, which are classified as silty-clay-loam represent only the lower-most buried Bk horizon at 75-115 cm (samples: 2775,2776 in Table 4). In Gilat most of the profile is concentrated around the boundary between silt-loam and loam classifications, with the exception of the lower-most sample at 130 cm which contain more silt and probably represents a pleistocenic buried soil.

Table 3 Soil samples from Gilat monitoring station profile

Depth * (cm)	Horizon	Sample		Bulk					Rosetta soil parameter predictions	
		ID	Depth** (cm)	CaCo3 (%)	Density (g/cm ³)	Clay % ***	silt %	san d %	FC	θ _r
0-10	A	2868	10	12.7	1.06	17.9	51.8	30.3	0.19	0.069
10-30	AB	2861	20	12.7	1.12	17.6	50.8	31.7	0.19	0.066
		2867	27	13.0	1.35	21.2	49.3	29.5	0.21	0.068
30-55	B	2864	40	13.3	1.43	23.6	48.9	27.5	0.22	0.070
		2866	40	12.4	1.37	23.1	47.7	29.2	0.22	0.070
		2865	60	14.0	1.46	24.7	47.9	27.4	0.23	0.071
55-100	B-Bk	2862	80	12.9	1.52	22.2	49.9	28.0	0.21	0.065
		2869	90	14.9	1.45	20.0	50.2	29.7	0.20	0.063
100- 140	Bk	2863	110	17.5	1.42	22.8	51.3	25.9	0.21	0.069
		2870	130	23.5	1.48	22.5	58.8	18.7	0.21	0.070

Table 4 Soil samples from Sde boker monitoring station profile

Depth * (cm)	Horizon	Sample		Bulk					Rosetta soil parameter predictions	
		ID	Depth (cm)	CaCo3 (%)	Density (g/cm ³)	Clay % ***	Silt %	Sand %	FC	θ _r
0-15	A	2769	0-3	24.8	-	14.34	43.03	42.63	0.21	0.052
		2770	3-6	11.9	-	15.84	36.85	47.31	0.22	0.054
		2771	6-15	22.1	-	22.51	51.47	26.02	0.22	0.071
		2772	15-30	24.9	-	22.40	55.46	22.13	0.21	0.068
15-50	Bk1	2871	25**	24.2	1.48	17.93	55.71	26.36	0.19	0.060
		2773	30-50	25.0	-	23.17	54.77	22.06	0.21	0.075
		2873	35**	22.1	1.25	20.55	58.55	20.89	0.20	0.072
50-75	Bk2	2774	50-75	27.7	-	24.68	54.74	20.58	0.22	0.074
		2872	60**	32.6	1.42	22.13	59.62	18.25	0.21	0.071
75-115	Bbkm	2775	75-90	37.1	-	30.72	56.65	12.64	0.26	0.086
		2776	90-115	38.8	-	37.23	50.76	12.01	0.29	0.094

* The profile was visible down to 140 cm for the Gilat site, and to 120 for the Sde Boker site

** Sample depth indicate middle of 5 cm diameter samples

*** Clay fraction is defined as <6 micron

5.1.2 Analyses of water content retrieved from monitoring stations

Soil water content measured by the sensors and calculated from soil samples is summarized in Tables 5 and 6. The highest water content measured by the sensors was far below saturation and close to estimated FC water content. The lowermost water content was higher in the deeper layers (closer to estimations of θ_r with the Rosseta model) and around estimated θ_r ($0.02 \text{ cm}^3/\text{cm}^3$ of Mualem, 1976) at the shallow layers. Differences in water content between sensors located at similar depth were relatively high ($0.02\text{-}0.05 \text{ cm}^3/\text{cm}^3$; depending on the water content range), however, the behaviors of sensors from similar depths are similar with respect to the changes in water content, timing and rates (see figure in Appendix IV.III).

Table 5 Gilat monitoring station : Water contents (cm^3/cm^3)					
Sample/Sensor Depth* (cm)	Soil samples		Sensors measurements		
	ID	Sample Water Content at 5.1.17	Sensors Water Content at 5.1-20.1.17	maximal	minimal
10	2868	0.17	0.12-0.10	0.21-0.16	0.02-0.025
20	2861	0.16			
27	2867	0.15	0.16	0.215	0.07
40	2864	0.08			
40	2866	0.07	0.14-0.09	0.23-0.16	0.076-0.12
60	2865	0.09	0.11	0.173	0.1
80	2862	0.10	0.12	0.15	0.11
90	2869	0.10			
110	2863	0.11			
130	2870	0.13			

Table 6 Sde Boker monitoring station : Water contents (cm^3/cm^3)					
Sample/Sensor Depth* (cm)	soil samples		Sensors A measurements		
	ID	Sample Water Content at 8.11.17	Sensors Water Content at 6.12.17-20.1.18	maximal	minimal
0-3	2769				
3-6	2770				
6-15	2771		0.08-0.11	0.21-0.23	0.08-0.12
15-30	2772				
25*	2871	0.05	0.10	0.15-0.21	0.13-0.14
30-50	2773				
*35	2873	0.05	0.11-0.14	0.15-0.11	0.14-0.12
50-75	2774				
60*	2872	0.09	0.12	0.13	0.13
75-90	2775				
90-115	2776				

5.1.3 Calibration-validation

Calibration and validation were achieved by comparing the modeled and measured water content profiles at two dates after similar periods of wet and dry days (procedure and methods explained in Appendix IV). The optimal set of parameters was found for: $K_c=0.6$, $FC=0.19 \text{ cm}^3/\text{cm}^3$. Therefore, $WHC=FC-\theta_r=0.17 \text{ cm}^3/\text{cm}^3$. Mean absolute difference and root mean square difference for optimal parameters are around 1 mm of water content (Figure 13), which is $0.0025 \text{ cm}^3/\text{cm}^3$ of volumetric water content error for 4 cm compartments. The WDs that are consistent with sensors data in SETA and SETB periods of the calibration, and this set of parameters also predicted the expected shape of the water content distribution, where, at shallow and deeper layers the water contents were lower compared with the slow drying wet layers in the middle of the profile (Figure 13).

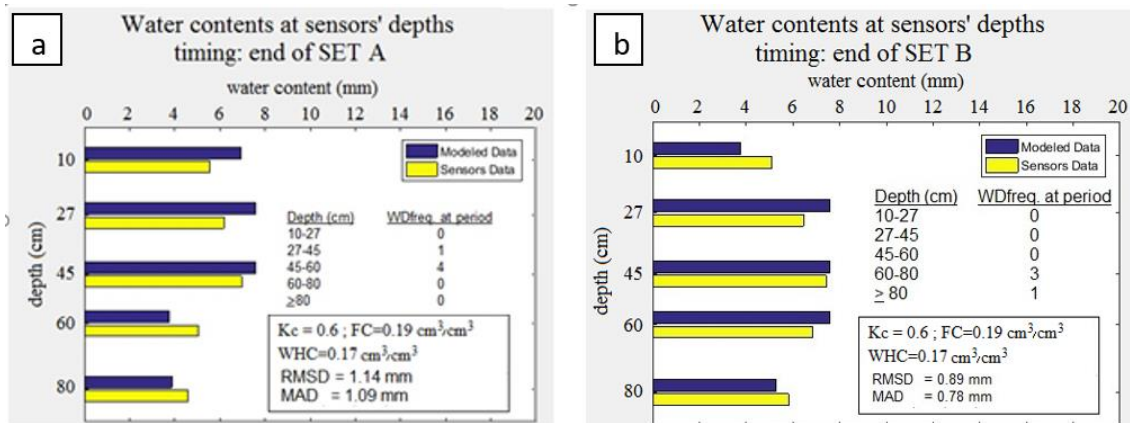


Figure 13 Results of the compartment model (a) calibration and (b) validation for optimal parameters in Gilat.

5.1.4 Water distribution properties

Figure 14 displays results for simulations of various long-term soil water distribution properties. Inputs for the simulations were the calibrated parameters, measured data-series of rainfall from meteorological stations in Be'eri, Gilat and Sde Boker, and synthetic PET series based on the PET generator. Lack of appropriate measurements of PET data forced the usage of synthetic simulations. Properties on display are: the distribution of long term water flow with depth; the distribution of wet zones in the soil profile, where the compartment held count of the length of time that each layer in the soil was filled to the FC water content; percentiles of wetting depths as counted for all rain days, and percentiles of the seasonal maximum for each year of the simulation. For all three sites, the depth to known carbonate horizons correlated with the depths where about 30% of

the rainfall total passed through- Index30, with the MeanWD and with 80th percentile of wetting depths- WDp80, suggesting that these variables can serve as potential proxies for carbonate horizons.

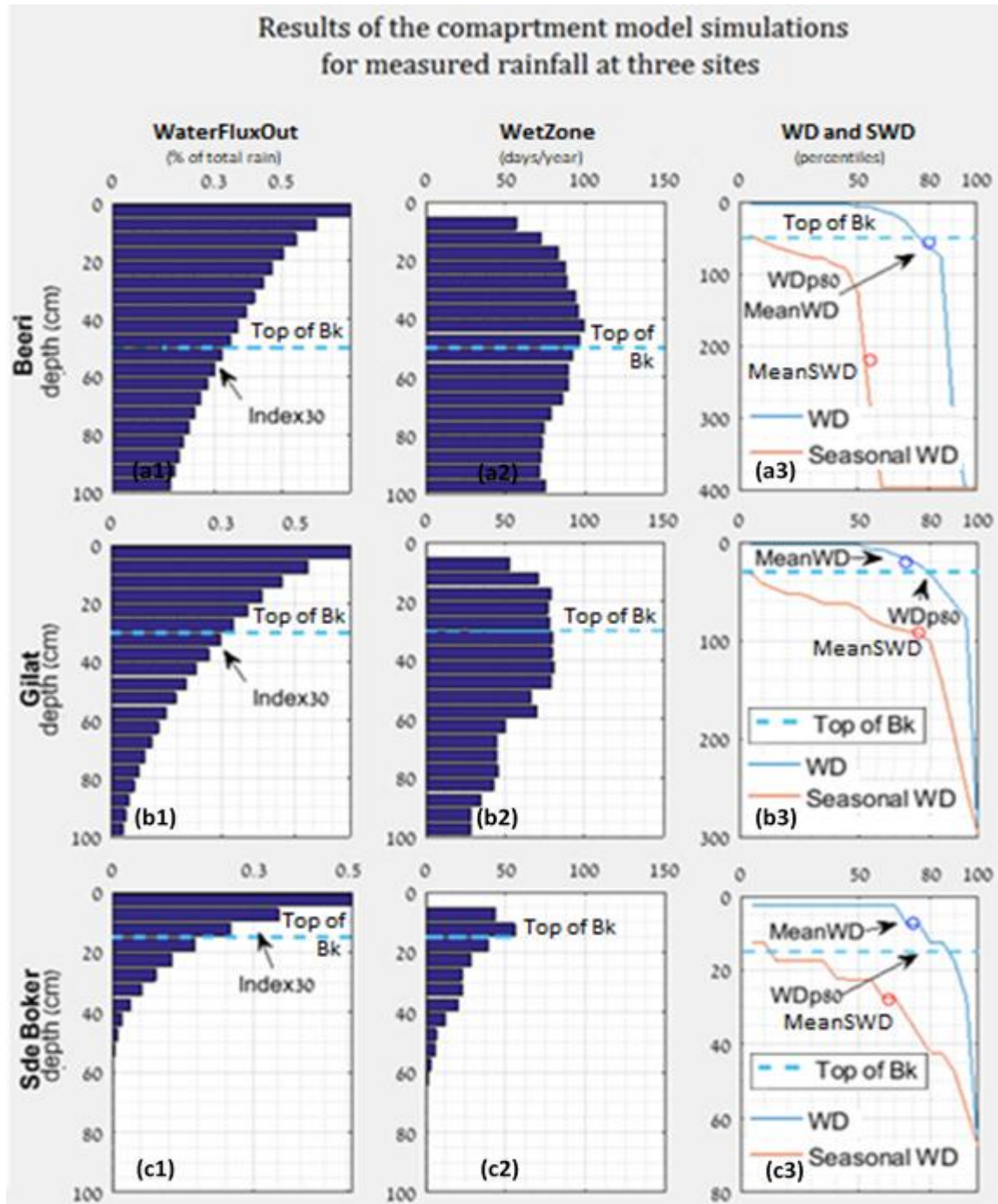


Figure 14 Initial results of the compartment model predict association of soil water distribution properties with depths to Bk in Sde Boker, Gilat and Be'eri. The distributions are illustrated in form of (a1,b1,c1) – water fluxes ('WaterFluxOut'); (a2,b2,c2) durations of high water contents ('WetZone'); and (a3,b3,c3)–WD and SeasonalWD distributions. These were simulated with measured rainfall series (daily data of 40-70 years periods, gathered from meteorological stations in each site). Depth of top of carbonate horizons (Bk) is associated with depth where WaterFluxOut of the layer is about 30% of the total rainfall (Index30 at a1,b1,c1); longer periods of the WetZone (in 2,b2,c2); with the depth of 80th percentile of wetting depths and with the mean wetting depth (WDp80 and MeanWD in a3,b3,c3).

Local sensitivity of Index30 and WDp80 to the calibrated parameters was tested for the local effect of changing the parameter with $\pm 10\%$ (Table 7).

Table 7 Local sensitivities of the three potential proxies to the calibrated parameters – results from simulations for rainfall of Gilat meteorological station.

Gilat or Mishmar HaNegev: depth to carbonate horizon: 30cm						
Change in parameters	depth of index30 (cm)	err (%)	WDp80	err (%)	MeanWD (cm)	err (%)
no change:	32		33		20	
FC-10%	35	7%	38	15%	24	21%
FC+10%	30	-6%	33	0%	18	-11%
Kc-10%	35	10%	38	15%	23	15%
Kc+10%	30	-9%	33	0%	18	-8%
T.M.Depth-10%	31	-5%	33	0%	21	5%
T.M.Depth+10%	34	5%	38	15%	20	-1%

For Sde Boker and Be'eri, the effect of changing the above parameters with $\pm 10\%$ resulted with changes in the depths of potential proxies by no more than 10%, not including the effect of Kc over the WDp80 in Sde Boker where an increase of Kc by 10% resulted with a shallower proxy by 36%, which translates to only 5cm.

5.2 The Rainfall Generator

Statistics of the synthetic rainfall properties derived from the rainfall generator resemble the properties of the meteorological data set, and therefore seem to represent the current climate in Gilat. The results of the synthetic data were tested using 100 simulations of 42 years of rainfall, similar to the period of the measured series (1953-1996). The percentiles of daily depths and MAR were plotted to give a visual representation of the distributions of these properties for each simulation and for the measured data (Figure 14).

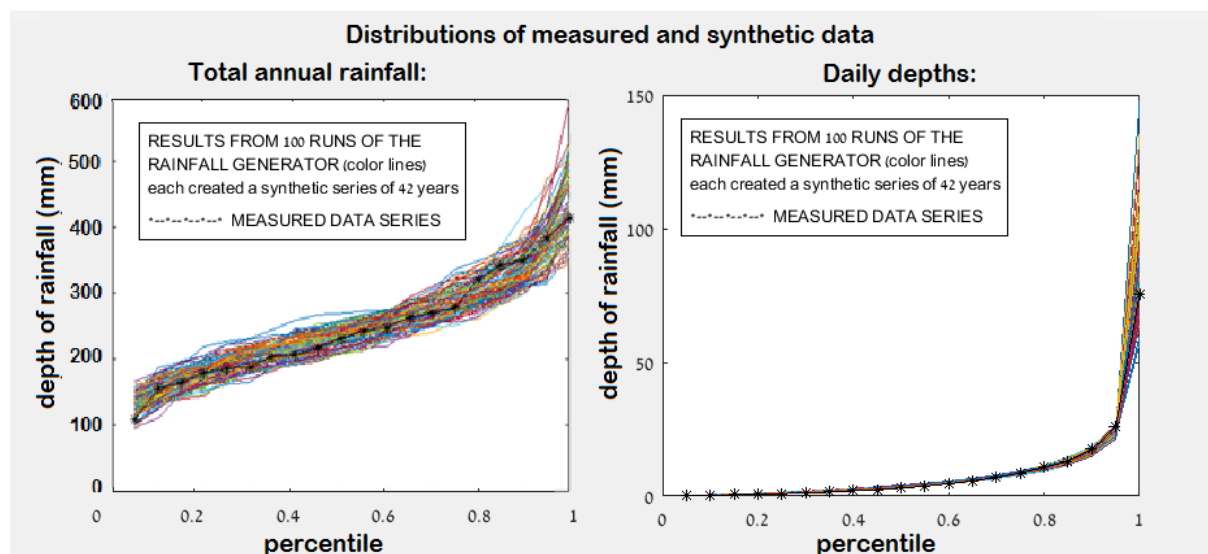


Figure 15 Validation of the rainfall generator for weather in Gilat: Distributions of MAR and mean daily depths of 100 synthetic series (in color) compared with measured rainfall series in Gilat (black stars) – on the left are the distributions of MAR, and on the right are the distributions of the mean daily depths.

Other properties were also compared between the measured series and each of the 100 simulations using means and standard deviations. T, F and K-S tests were taken to establish confidence in the efficiency of the synthetic data to represent the climate properties in Gilat. The simulations produced data with very similar properties and agreed with the statistics of the measured data. Table 8 summarizes the statistics and percentage of success in the statistical tests. For the large majority of the simulations and rainfall distribution properties, statistical tests did not reject the possibility that the measured and synthetic data represent random samples of the climate in Gilat at a 5% significance level. Results of the statistics tests in Table 8 are represented by the percentage of synthetic series, for which this hypothesis was not rejected, and therefore were considered as success in the tests.

Table 8 properties of the measured data from Gilat meteorological station (IMS), and simulated data with the rainfall generator. Distributions with scores of 70% and higher for the T,F and KS statistical tests, were highlighted for the convenience of the reader.

site	Gilat		42 years of dataX100 Parameters for synthetic series: A=5.45 B=0.76 Fdry=1 Fwet=1					
data-series	measured		Synthetic			T	F	K S
Distributions	mean	std	mean	std	err	% not rejected		
Mean annual rainfall (mm)	237.6	81.2	239.8	73.2	1%	100	93	99
Daily depths (mm)	6.5	9	6.5	8.5	0%	100	55	3
Annual mean daily depth (mm)	6.5	2	6.5	1.4	0%	100	97	100
Number of wet days per year	36.6	9	36.9	7.6	1%	99	89	99
Number of rain events per year	19.0	4	19.6	3.5	4%	98	73	98
Events depths (mm)	13.0	21	12.2	16.8	-6%	97	2	0
Annual mean events depths (mm)	12.8	4	12.3	3.4	-4%	100	57	100
Events durations (days)	1.9	1	1.9	1.4	-3%	95	39	59
Annual mean events durations (days)	1.9	0.4	1.9	0.3	-3%	98	86	98
Frequency of extreme daily depths (p99Gilat)	0.4	1	0.3	0.6	-15%	98	81	100
Extreme daily depth $\geq 99^{\text{th}}$ percentile (mm)	42.7		40.6	2.8	-5%			
Dry Spells (days) 0.1mm event separation criterion	9.8	8.3	11.4	10.7	16%	2	0	0
Annual mean dry spells (days) - depth of event separation criterion: 0.1 mm	10.3	3	11.7	2.5	14%	23	85	5
Annual std of dry spells (days) - depth of event separation criterion: 0.1 mm	8.1	4	10.2	4.0	25%	24	86	25
Dry Spells (days) 2mm event separation criterion	13.1	12	13.0	12.5	-1%	100	75	88
Annual mean dry spells (days) - depth of event separation criterion: 2 mm	14.3	6	13.4	3.4	-6%	100	2	100
Annual std of dry spells (days) - depth of event separation criterion: 2 mm	12.1	7	12.0	4.8	-1%	100	23	98

Local sensitivity of the rainfall distribution properties to the generator input parameters are presented in Figure 16. This sensitivity is quantified around the optimal set of parameters for the rainfall in Gilat ($F_d=F_w=1$, $A= 5.54\text{mm}$, $B=0.76$). Uncertainty of the rainfall mean properties was reduced from 18-25% to 5-10% for simulations of 50 and 500 years periods, respectively. This uncertainty results from the stochastic nature of the model and is viewed by the variability of the mean properties of the rainfall.

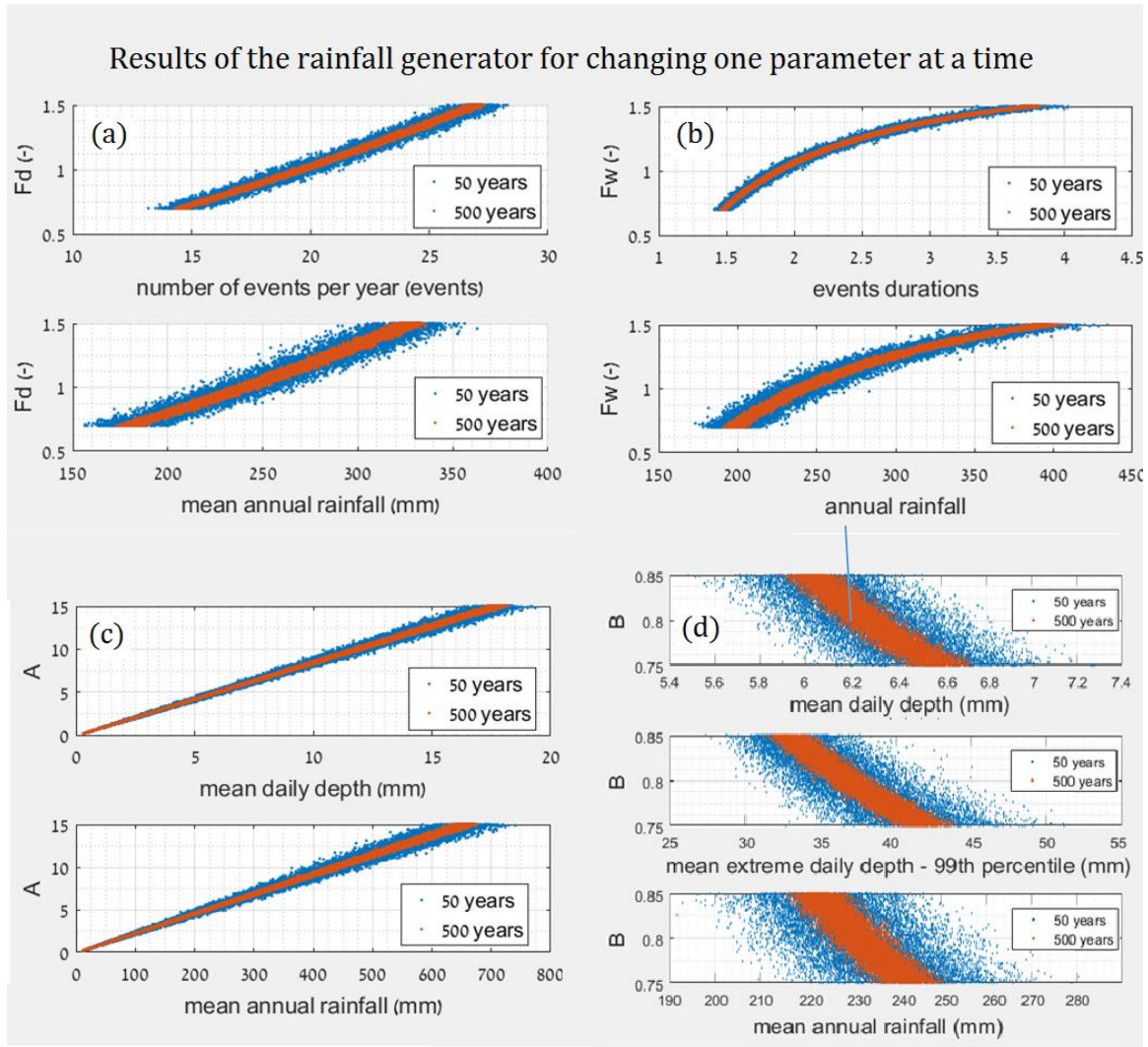


Figure 16 Local sensitivity and correlations between rainfall parameters and mean rainfall properties: (a) the mean number of events per year was correlated with F_d parameter; (b) the mean event duration with the F_w parameter, (c) the mean daily depth with the scale parameter (A) of the weibull distribution for daily depth. (d) Sensitivity was also evaluated for the effect of the shape parameter (B). All results are for changing only one parameter while the others were fixed on the optimal set for the Gilat rainfalls ($F_d=F_w=1$, $A= 5.54\text{mm}$, $B=0.76$). For any change in the parameters, the rainfall was simulated 100 times giving a range of uncertainty of the model for rainfall properties that is the result of the stochastic nature of the model, and the chosen distribution functions. The range for F_d (a), and F_w (b), are the factors over the probability Gaussian for WAD and WAW days respectively was 0.7-1.5 with intervals of 0.01. the ranges for the scale (A in c), and shape (B in d) parameters of the Weibull distribution for daily depths were 0.2-15mm with 0.1 mm intervals for A , and 0.75-0.85 with 0.001 intervals for B .

Functional relationships between parameters of the rainfall generator and the mean properties of the simulated rainfall derived by curve fitting (Figure 16) The variability of B in the study site is small, differences from the evaluated B for Gilat are: in Sde Boker- up to 0.3%; in Be'er Sheva – up to 3%, and in Be'eri- up to 6%. Therefore the B parameter was fixed on the value estimated for Gilat, and input parameters for simulations of rainfall in the other three sites are given by the relationships of Fd, Fw and A given in Table 9, and mean weather properties given in Table 1.

Table 9 Functional relationships of parameters A, Fd and Fw with the appropriate rainfall properties for B=0.76mm, derived from the results in Figure 16. The appropriate rainfall parameters for 3 meteorological stations in the northern and central Negev were calculated.

Function	R ²	RMSE	Sde Boker	Beer Sheva	Be'eri
A = 0.8502(mean daily depth)-0.08192	0.9996	0.08685	2.78	4.03	7.52
Fd = 0.06441(mean events in year)-0.2562	0.9968	0.01328	0.76	1.06	1.02
Fw = -1.897(mean events durations) ^(-1.187) +1.896	0.9991	0.007093	0.88	1.03	1.06

Two results of the rainfall generator for Be'eri and Beer-Sheva sites are presented in Figure 15 as examples. The parameters for the simulations were chosen with the formulas from Table 9, and using measured data series to draw the required input values for properties of events number, durations and mean daily depths. While the events number (per year) and the events durations were simulated very well, setting the shape parameter (B) at a fixed value compatible with Gilat daily rainfall distribution resulted with some discrepancies for the daily depths, which also affected the MAR. The simulations for Beer, Beer-Sheva and Sde-Boker sites over-estimated the mean daily and MAR in normal and dry years, and to a small extent it under-estimated rainfall in extreme days and years. The mean errors for MAR properties such as events per year, events durations, and mean dailies are small, in the range of 1-5%, and the synthetic series seem to represent the rainfall of Be'eri, Gilat, Be'er-Sheva and Sde-Boker sites. Test statistics and comparison of the rainfall properties distributions of all four sites are presented in Appendix IV.

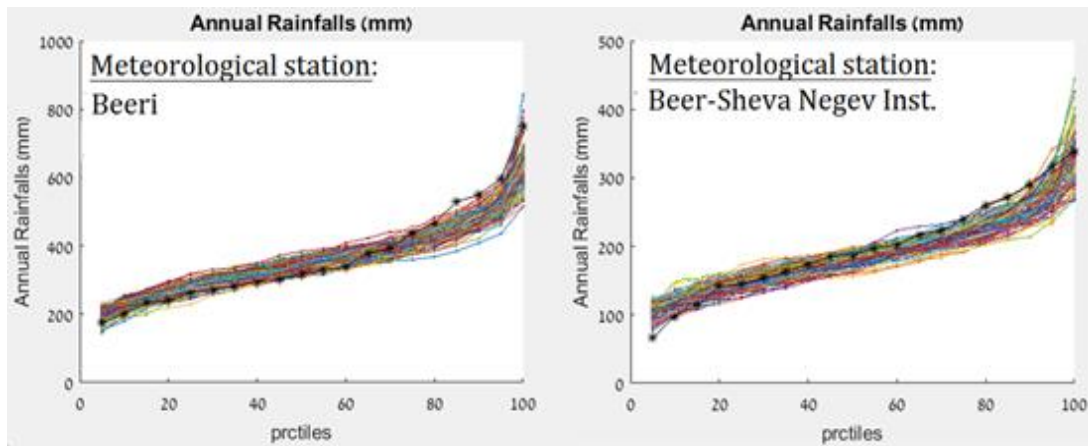


Figure 17 Validation results of the rainfall generator in Be'er-Sheva and Be'eri – examples of the model's performance for un-calibrated locations in the study site. Distributions of MAR from 100 synthetic series (colored lines) compared with MAR of measured data series (black stars) for Be'eri (left) and Beer Sheva (right) sites. Input parameters for the simulations were calculated using rainfall properties measured at the appropriate meteorological stations (Table 1) and relationships in Table 9. Simulations in Be'eri are with greater discrepancies than in Beer-Sheva. Both under-estimated wetter years in most of the simulations. However, the differences are not large and some of the simulations do appear similar to the measured data.

5.3 PET Generator

The PET generator requires an input of a rainfall data series to assign daily PETs for DAD, DAW, WAD, WAW types of days, for each month of the year. The performance of the PET generator was tested for deriving mean and standard deviations of monthly PETs similar to a measured one. The input to the PET generator was a 5000 years long synthetic rainfall data series, based on rainfall generator, with parameters for Gilat meteorological station. The mean and standard deviation of the monthly PET of a synthetic series and a measured series are plotted in Figure 17. The standard deviation is very low in the synthetic series compared with the 16 years long measured series.

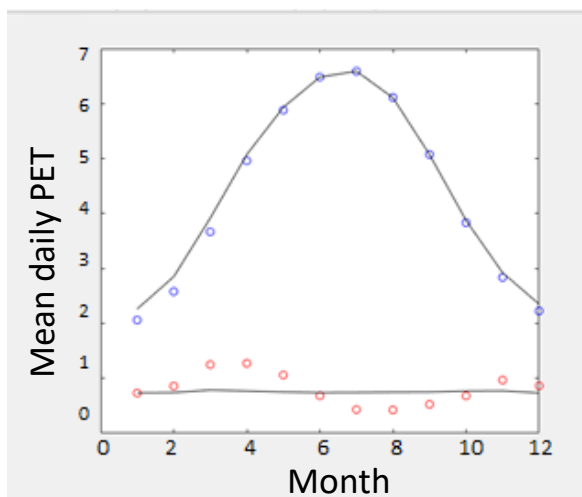


Figure 18 Validation results of the PET generator for Gilat site: monthly means (blue) and standard deviations (red) of measured (circles) and synthetic (black lines) daily PETs.

5.4 Geographical trends of water distribution properties and MAR

Mean WD, WDp80 and Index30 were found to correlate well with top of Bk horizon (Figure 14), when using measured rainfall series in Be'eri, Gilat and Sde Boker of 40-70yrs. I re-examined these correlations, this time using synthetic rainfall data of 500 years periods simulated by the rainfall generator for Be'eri (340 mm/yr), Gilat (240 mm/yr), Beer Sheva (180 mm/yr) and Sde Boker (90 mm/yr). MeanSWD, SWDp80 and Index3 seem to follow the trend of depths to By horizons. The proxies were plotted on Dan and Yaalon (1982) diagram using ten repetitions of 500 years-long simulations (Figure 18).

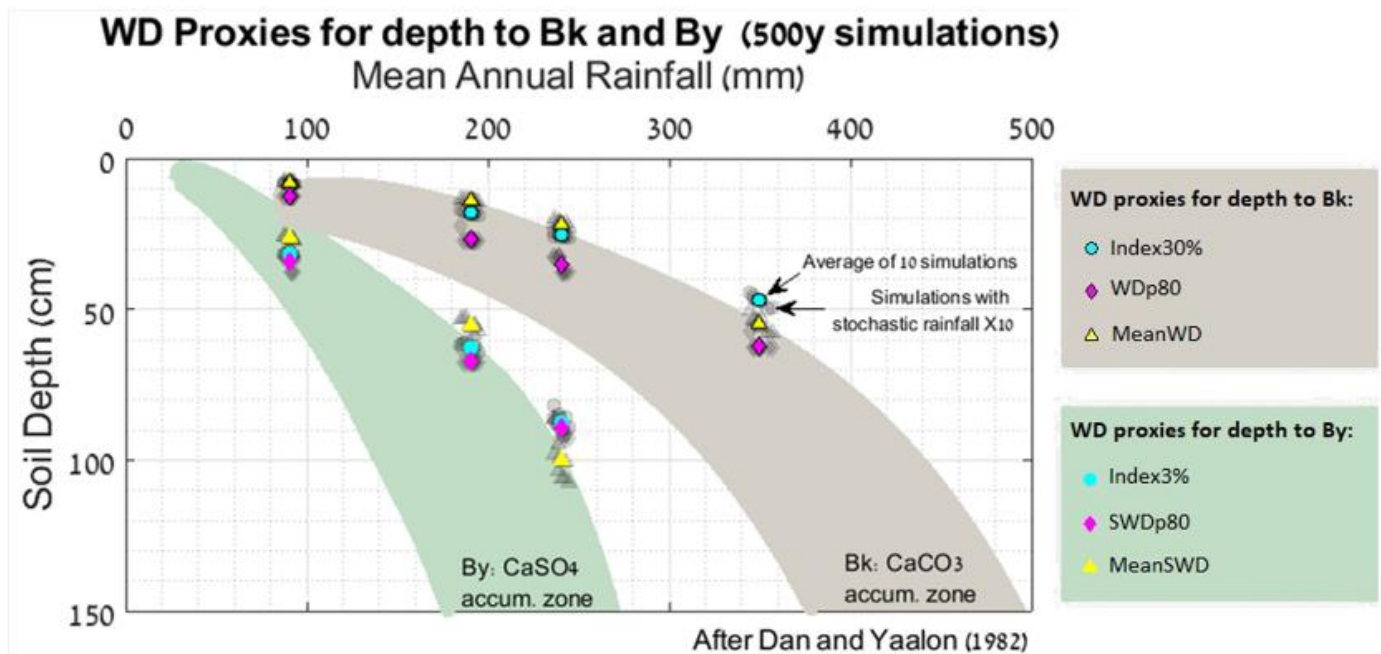


Figure 19 Trends of depths to Bk/By in Israel (after Dan and Yaalon, 1982) reproduced by WD results of the compartment model simulations - using long term synthetic weather for 4 sites in the Negev.

All proxies seem to follow the schematic trend of Dan and Yaalon (1982). This reinforces the legitimacy of the proxies and validate the combined compartment model and the weather generator. The variability of the results, caused by the stochastic nature of the rainfall and evaporation, does not affect the trends, and proxies that were simulated for the same site with similar properties, are deeper with small differences and still correlate with the MAR. 5000 years simulations were also conducted, producing results that are averaged to the same depths as the 500 years simulations, with less rainfall variability, all seem to indicate similar values. Yet, within five repetitions of the 5000 years simulations, WDp80 had some differences of up to 5 cm depths, and the results of 500 years simulations vary in a range of up to 20 cm for the suggested proxies depths to By horizons.

The latter seem to be affected mostly by its high sensitivity to the differences in the simulated rainfalls and therefore might suggest realistic behavior of depths to By horizons.

MeanWD and MeanSWD are the most robust of all the potential proxies, having very similar depths with short and long term simulations, suggesting that they are less sensitive to variations in climate because of the mathematical qualities of the mean. These proxies seem to have the best fit to the curve.

5.5 Sensitivity analysis for carbonate and gypsum proxies

5.5.1 Local sensitivity

Four sets of rainfall parameters were used to simulate the weather in Be'eri, Gilat, Beer Sheva and Sde Boker (*Table 9*). In *Figure 20*, local effects of changing any parameter with 20% on the depths of MeanWD are presented. The effects vary from 2cm in Sde Boker to 24 cm in Be'eri. The effects increase with MAR (*Figure 21.a-b*). However, the deepening or shallowing of a proxy is more correlated with the effect of the parameters on the mean event depths (*Figure 21.b-d*).

Comparing maximal absolute difference of MeanWD, Index30 with weather properties suggest a closer relationship between increases in EventsDepth and Index30. Index 30 is also more sensitive to B parameter that affects the mean and tail of the daily depths, comparing A parameter that mostly affects the mean, whereas effects on MeanWD are opposite (*Figure 21*).

Parameters A, B and Fw all affect both mean event depth and MAR by increasing mean daily depths, extreme daily depths or mean event duration. The control of these parameters on deepening and shallowing of the proxies are not symmetrical. For deepening of MeanWD, Fw that mostly control the event durations is more effective than A and B parameters, even though MAR and EventsDepth experienced similar or slightly greater increase by the changes in A or B parameters. And although B-20% cause greater increase to MAR and to mean event depth, its effect on the MeanWD is almost 2-3 times lower than A's. That is not the case for Index30 – for which their effects are similar (*Appendix VI*).

For shallowing of MeanWD, A, which has greater effect over the mean daily depth, is the most effective parameter, although B+20% cause greater changes to MAR, EventsDepth and Index30 (Appendix VI). However, out of the rainfall parameters, B+20% has the greatest shallowing and moderating effect over the depths and slope of the trend of MeanWD with MAR. Suggesting that if MAR is kept constant while less extreme rainfalls occurs the depths to Bk horizons will be shallower. This emphasizes the importance of extreme events to WDs and depths to Bk horizons. However, for deepening of MeanWD, Event durations and A parameter are more effective.

PET is the only variable that changes independently to MAR. Thus decreasing F_{PET} by 20% (without any change in rainfall properties) cause deepening of both MeanWD and Index30 by 10-20% (Figure 21).

Fd is the parameter most affecting EventsN. It has insignificant effects on the other rainfall properties that control the mean event depths, but it does affect the MAR. In Figure 22 the results of MeanWD from simulations of 20% changes in weather parameters for each site were plotted against the MAR instead of its geographic location (as in Figure 20). This emphasizes the effects of weather parameters and rainfall properties on the trend with MAR. The effects of Fd- or EventsN (red lines in Figure 22), and F_{PET} cause the greatest difference to the trend, which implies that for the same annual rainfalls, depths of Bk horizons are most sensitive to EventsN and PET. The rainfall generator is structured so that EventsN and EventsDepths are determined by different parameters and therefore the interactions of their effects are weak.

Figure 23 illustrates how MeanWD would trend differently with MAR for variations of three different rainfall parameters. In the northern Negev, the regional transect of MAR is mainly a result of the change in A affecting MAR. In areas where the main property that changes would be the EventsN, the trend of Bk horizons with MAR would be expected to be shallower, and more subtle.

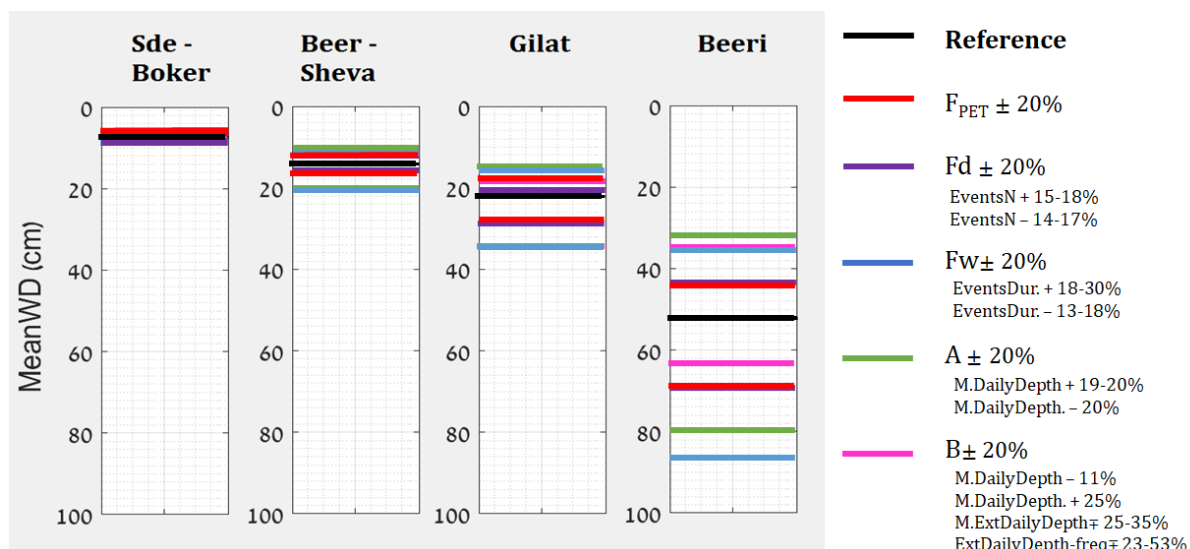


Figure 20 Local sensitivity of MeanWD to 20% change in the model's weather parameters. The effects of the change of parameter to the most influenced weather properties is given in the legend on the right. EventsN is the mean annual number of events (events/year); EventsDur. Is the mean event duration (days); M.DailyDepth is the mean daily depth (mm); M.ExtDailyDepth is the mean of 99th percentile taken from 100 rainfall simulations (mm); Ext.DailyDepth-freq is the mean frequency of occurrences of Ext.DailyDepth (days/year) taken from 100 rainfall simulations.

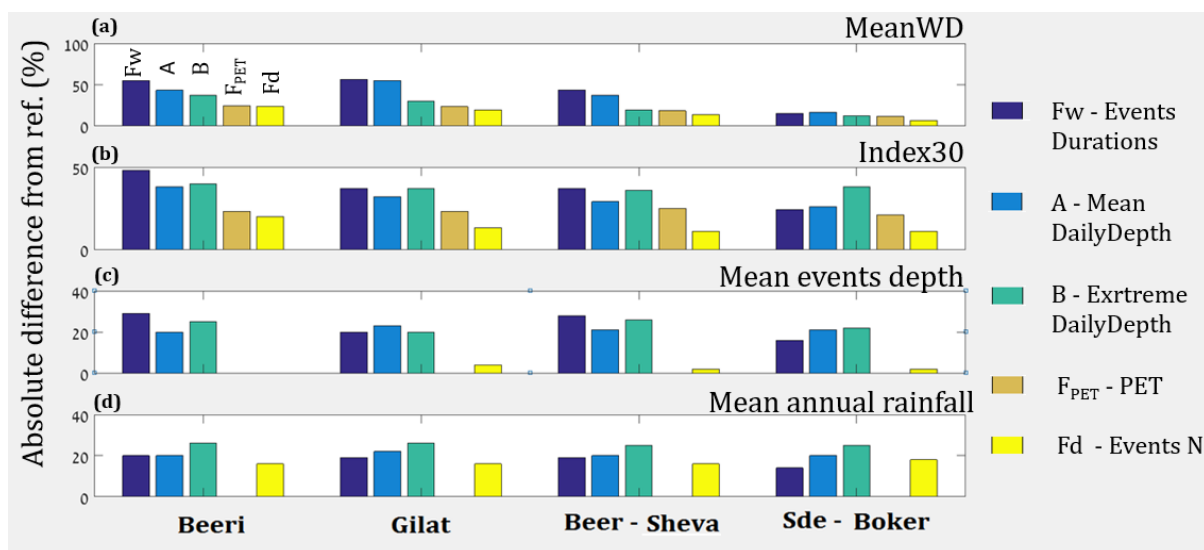


Figure 21 Local sensitivity - max absolute difference (in %) of Bk proxies and rainfall distribution properties to 20% changes in weather parameters. Prescribed in the legend: the weather parameter causing the effect and the rainfall property most affected by it.

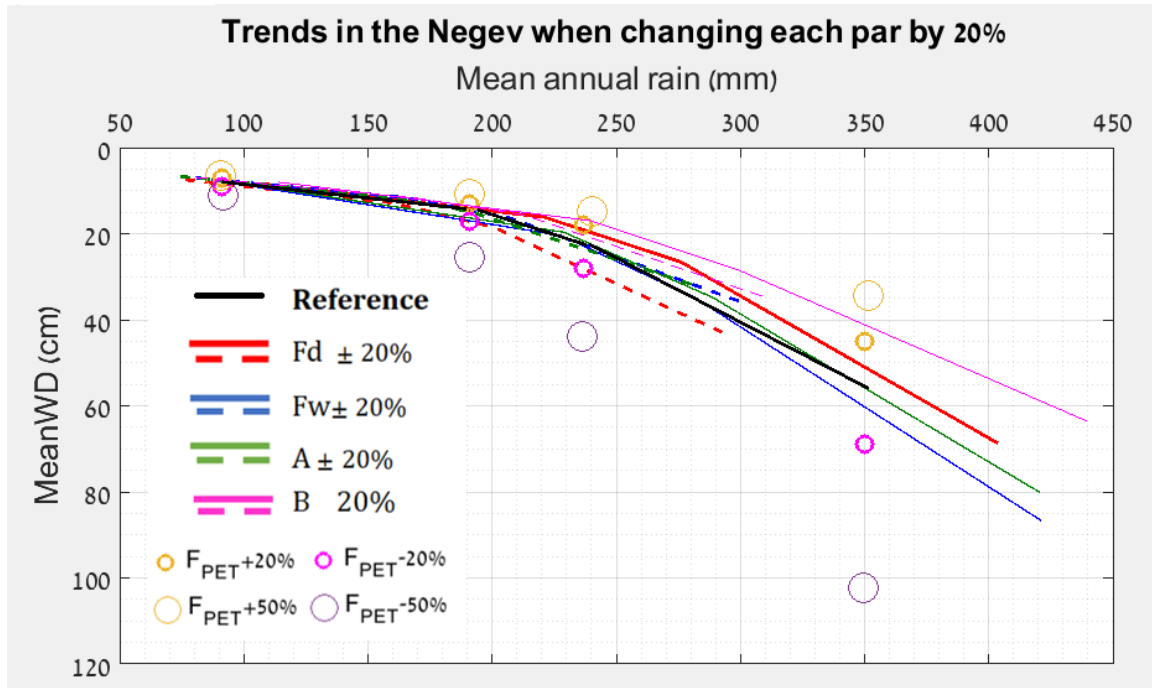


Figure 22 Effects of 20% change in weather parameters on the regional trend of MeanWD with the MAR: each line represent a trend of MeanWD with MAR simulated with 20% change in one of the properties: number of events per year (controlled by Fd- red); mean event duration (controlled by Ew in blue); mean daily depth (controlled by A – green) and the factor over PET shown with yellow circles for 20% increase, and with purple circles for 20% decrease in the daily PET.

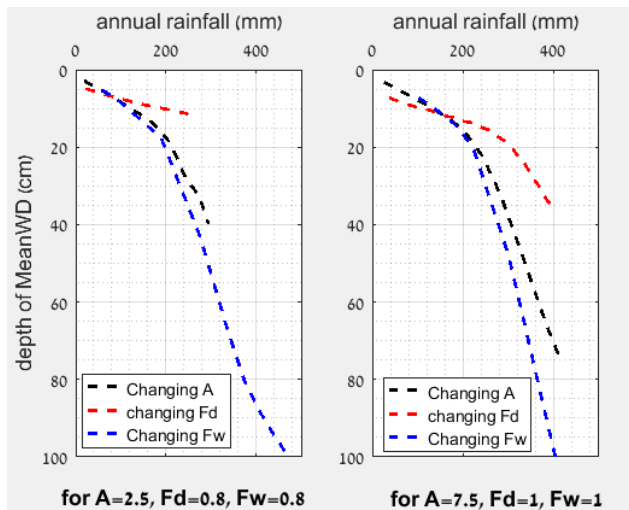


Figure 23 Local effect of rainfall parameters on the trending of MeanWD with MAR suggesting differences in the trending of depth to carbonate horizons for areas with different climates: Results of changing one rainfall parameter at a time around two fixed sets of parameters - approximating weather in Sde Boker (left) and Be'eri(right) . Increments of each rainfall parameter in the simulations are given in Table 2.

5.5.2 Global sensitivity analysis

The results of 1500 combinations of rainfall parameters for F_{PET} of 0.5, 1 and 1.5 are presented with MeanWD and MeanSWD proxies plotted against MAR. The results are displayed in colors yellow, blue, and magenta according to the appropriate F_{PET} on Figure 24. The proxies in the graphs can be read with cm length units (y-axis on the left), for soils with WHC of 0.17cm³/cm³, as assumed for the northern Negev, or, with general WHC units (y-axis in the right) to be translated for depths in soils with other water content properties.

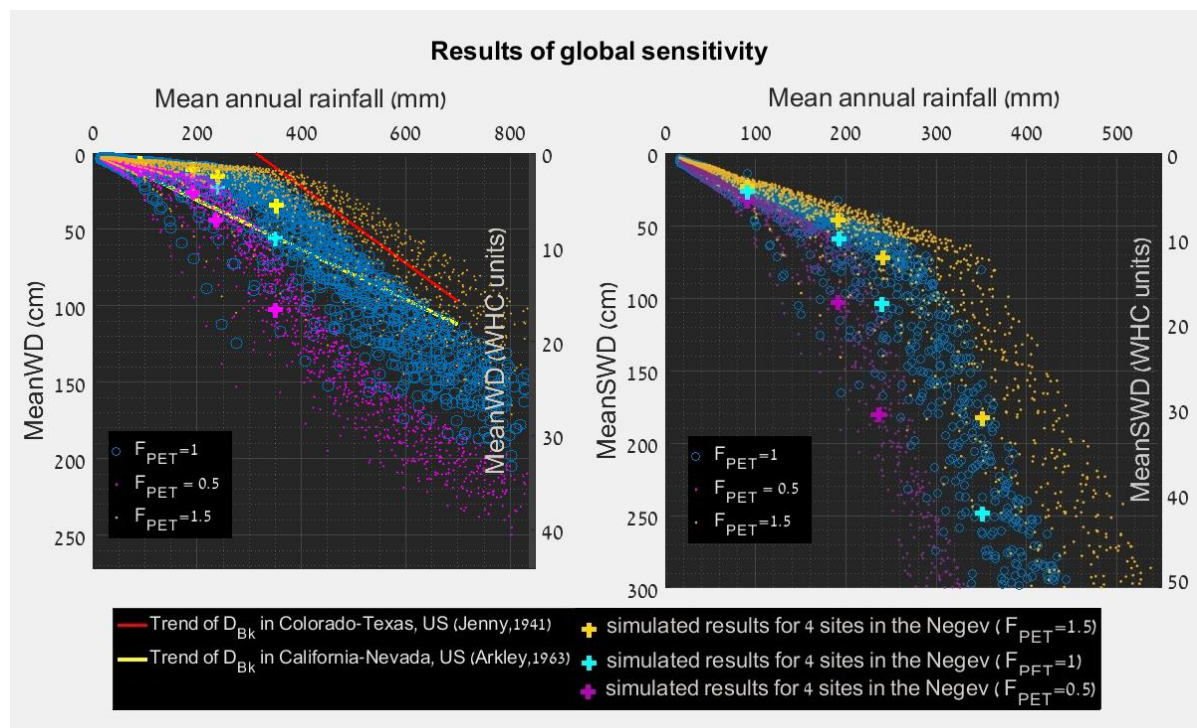


Figure 24 Global sensitivity analysis for the effect of rainfall and evaporation parameters on the depths to carbonate (left) and gypsum (right) proxies as a function of the mean annual rainfall: Results of about 1500 simulations with various combinations of rainfall parameters shown for three different PET factors. Local effects of the F_{PET} on MeanWD simulated for Sde-Boker (80-90mm), Beer-Sheva (190mm), Gilat (240mm) and Be'eri (350mm) are shown for reference. Bk trends found for summer (Jenny, H.J., and Leonard 1935) and winter (ARKLEY 1963) rainfalls fall in ranges of high and low F_{PET} results respectively.

Generally, MeanWD and MeanSWD deepens with MAR and with average decrease in PET. It is shallower for higher PETs. The control of MAR over depths of proxies is apparent, but the scatter suggest effects of other rainfall properties that vary within the scenarios (Figure 24, Figure 25). As seen in the local sensitivity results, the effects of any weather property on the proxy grows with MAR. MeanSWD is much more sensitive to weather than MeanWD (Figure 19, Figure 24).

The effect of PET on the depth of the Bk horizons can be dramatic. Although at ~300 mm/year, an increase F_{PET} by 50% results with shallower proxies by only 5-10 cm, a decrease of this variable by 50% results with about 40 cm deeper MeanWD. The effect of EventsN on MeanWD varies from 5 to 130 cm in the range of 20-400 mm of MAR (Figure 24). Figure 25 displays the relationship between MeanWD and MAR for current evaporation conditions as calibrated for Gilat ($F_{PET}=1$, $K_c=0.6$). Colors and sizes of circles in these diagrams indicate the mean number of annual rainfall events and mean event depth, respectively. This resulted with seemingly deeper and steeper bands of color for simulations with lower number of MAR events.

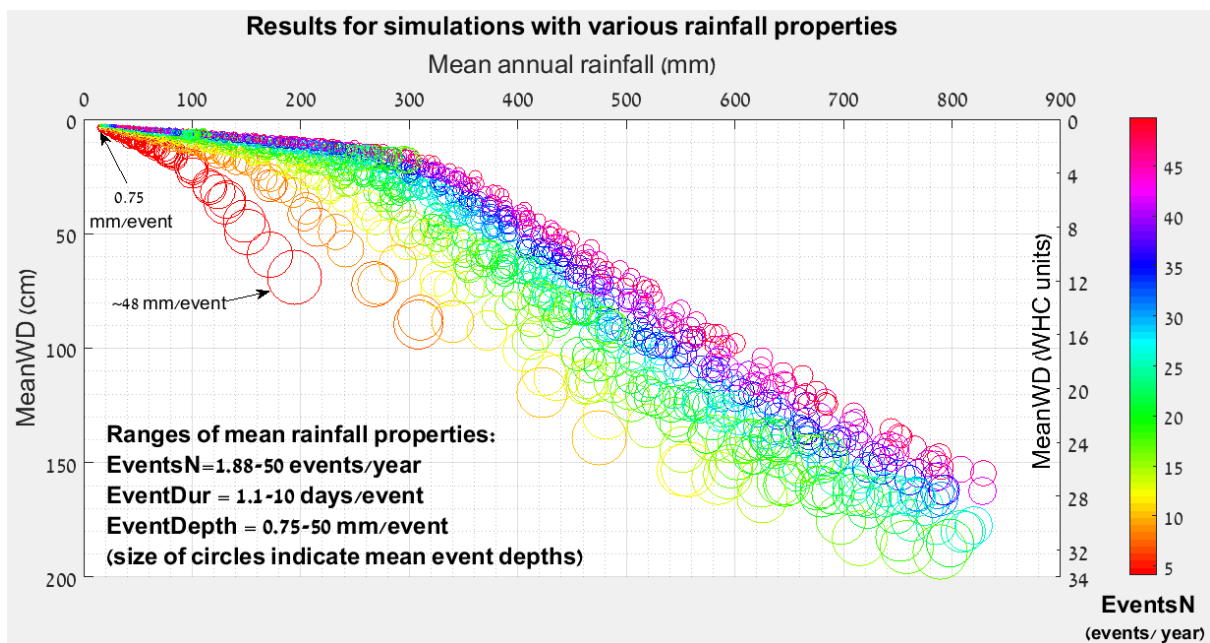


Figure 25 Results of simulations with various rainfall properties and constant PET ($K_c=0.6$, $F_{PET} = 1$ – as calibrated for Gilat site). The annual rainfall control the general trend, while a combined effect of the mean annual frequency of rainfall events (EventsN) and mean depths of events (EventDepth) cause scatter of up to 100cm. The effect is smaller for lower annuals. The effect is larger for simulations with low to medium frequency of events/year (<20 events/year).

The depth of the MeanWD can be determined by a combination of any two properties out of: EventsN, EventDepth and annual rainfall (e.g. - Figures 25,26).

Sensitivity of MeanWD with other rainfall properties are illustrated in Figures 25,26. In these figures, I have isolated results of $F_{PET}=1$, and relatively similar MAR (280 ± 30 mm) and plotted them against various rainfall properties. The range of MAR was chosen to allow for a combination of maximal number and variability of results and minimal range

of MAR. The mean number of events per year and the mean event depth control the depth of MeanWD and reduce the vertical scatter of the results of 260-310mm/year from about 70 cm (or 12 units of WHC) to up to 20cm (or about 3.5 units of WHC) (Figures 25-26).

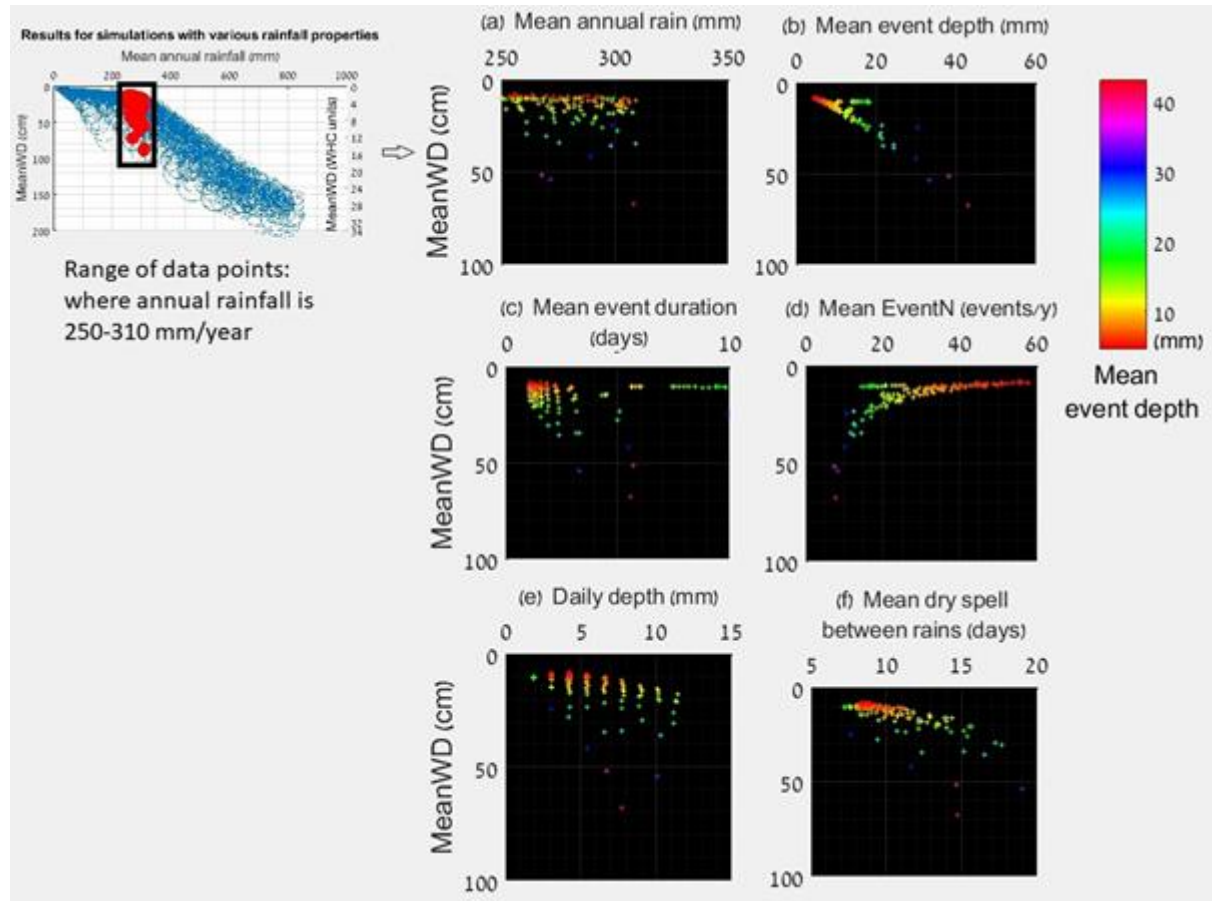


Figure 26 sensitivity of the MeanWD to 6 different properties of rainfall when mean annual is limited to 250-310mm and FPET=1. Colors represent the mean event depth which is positively correlated with the MeanWD. In plots b-d, few results are unaffected by the rainfall property and are limited to about 17cm depths- suggesting bi-modal behavior of the results.

Setting aside few unaffected results, the mean event depth is almost linearly correlated to the MeanWD according to Figure 26.b. It has the strongest control over the depth of the MeanWD. The mean number of events per year is negatively correlated with MeanWD and with the mean event depth, and presents similar bi-modal behavior with respect to the same "unaffected" results around 17cm depth. The rest of rainfall properties in Figure 26 affect MeanWD by interactions with each other that are reflected in the mean event depth property. For example, MAR divided by number of events per year equals mean event depth.

The so called "unaffected" results that can be viewed in Figure 26.b-d and in Figure 27 are MeanWDs that were simulated with small daily depths (<2 mm/day) and long event durations, although the event depth may be high enough, the daily evaporation would not allow these events to result with deeper WDs.

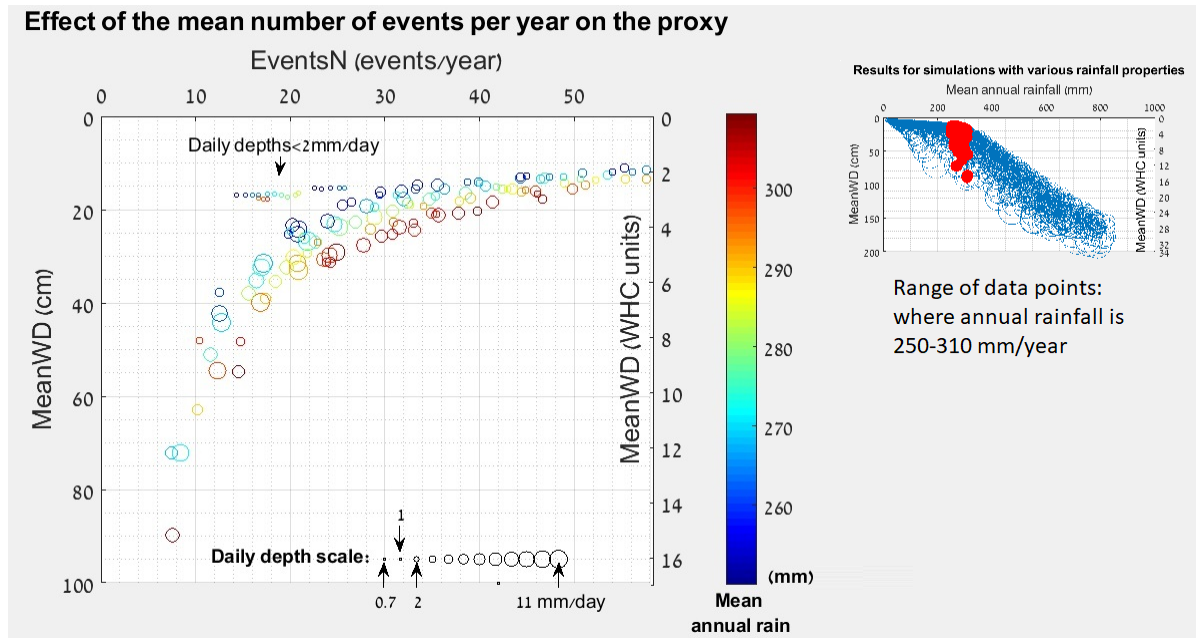


Figure 27 Results for MeanWD for simulations with low variability of MAR (range of 250-310mm/year) are strongly depended on the mean number of events per year (EventsN). Size of circles indicate the mean daily depth. Data points of daily depths < 2mm/day behave outside of the general trend and are less affected by EventsN.

6 Discussion

6.1 WD proxies for depths to Bk and By horizons

6.1.1 Validation of the framework

I found three long term WD properties that can serve as proxies for depth to Bk and three for depths to By horizons (Figure 19). The proxies, which were calculated from simulations of current weather scenarios in the Negev, Israel, correlate with MAR that is similar to the already observed relationship between MAR and depth to salts horizons (Dan and Yaalon, 1982). Generally, all proxies seem to be affected similarly by changes in mean properties of weather, but they differ in magnitude. I have presented results of MeanWD as an example for proxy for depth to Bk and results of MeanSWD as an example for proxy for depth to By (see section 5.5 in the Results chapter).

6.1.2 Proxies have different sensitivities to extremes vs. mean trades of weather

One of the possible applications of this study would be to explore the effects of extreme Vs. average weather properties on depths to Bk and By. There are many ways in which extremes can be simulated. I have examined only local effects of the B rainfall parameter on the proxies. As explained earlier, B is the shape parameter for the daily depth Weibull function, and it has greater influence over the tail of the distribution than its mean value. Although it was noted in the past that simulating extreme rainfall is important for reconstructing CaCO_3 profiles (Marion and Schlesinger, 1994; Marion *et al.*, 2008), it might not be important for estimating only the depth to the top of Bk horizon. The results of my simulations suggest that A and Fw parameters, which control Mean daily depths and the mean event duration in the rainfall generator, have larger effects than B on deepening of MeanWD and MeanSWD (Figure 21, Appendix VI). For WDp80, Index30, SWDp80 and Index3, changes in parameter B, are as effective or even more effective to proxis' depths. Additional work is required to test this with global sensitivity analysis and to compare calculated proxies with more records of depths to Bk/By horizons. This will allow a determination of which proxy is more appropriate and more universal for reconstructions of past weather properties and depths to soil horizons. And it will help to find suitable weather scenarios from depths to Bk records.

For depths to Bk horizons, extreme rainfall might be even more important than for depths to Bk because of its sensitivity to wetter years (Dan and Yaalon, 1982) and extreme events (Marion *et al.*, 2008).

6.1.3 Proxies for depths to Bk horizons

MeanWD, WDp80 and Index30 were found to indicate depths to Bk horizons in the northern Negev and trend with MAR as expected. The association between these proxies and the higher values of the "Wet Zone" (Figure 14) reinforces the proxies' validity. The longer an area of soil is wet, the higher its potential to host roots and biological activity. This has been noted to influence the carbonate solubility and affect the locations of Bk horizons (Schlesinger, 1985; Amit *et al.*, 2006). It also suggests that these proxies for depth to Bk horizons can be used as indices for soil water conditions in environmental and ecological studies, where, for example, it is important to understand how changes in climate may influence water availability to plants with different rooting depths or seedlings that require the soil to be wet enough for specific lengths of time.

Beyond different responses to extreme rainfalls (see 6.1.2), additional differences between the three proxies may favor one over the other. For example, MeanWD imitates the curve of Dan and Yaalon (1982) better, while the other proxies, Index30 and WDp80 trend with more moderation northward (Figure 19). This could be an effect of the discrepancies between the simulated and measured rainfalls in Be'eri (Figure 17), especially if Index30 is more sensitive to underrepresented extreme events. But it can also be a correction of an inaccurate scheme, because Index30 does estimate the recorded depth to Bk horizon in Be'eri correctly (at about 50cm).

MeanWD is defined with close resemblance to Arkley's (1963) proxy for depth to Bk (referred to as "*mean depth of water penetration*"), which was calculated for sites in California and Nevada, USA. This enforces MeanWD, as a suitable universal proxy for depths to Bk.

Some uncertainties of the results are inherent from the models assumptions. for example, The 4m soil profile limits the WD distribution and the MeanWD. This produced a moderation in the deepening of MeanWD with MAR at MAR > 400 mm/year (Figure 24, Figure 25), where WDs greater than 4 m are increasingly more frequent. Similarly, T.M.Depth of 1m limits most WDs to be either within the first 1m of the soil or at 4m, because compartments representing depths of 1-4m cannot dry up by the AET and once

it had reached capacity, at FC water content, the simulated water flow never stops within this range of depths and continues on to the lowermost compartment. This conceptual model is justified by theory and by physical modeling (Figure 8) but its influence on the WD is probably more subtle in reality. Thus, instead of a gradual decrease in the density of the results that are greater than 1m in depth, the deeper Index30 and WDp80 are indicated at depth > 4m (Appendix VII). The effect on MeanWD is not as obvious because it is smoothed by the mean.

Most of Bk horizons in the world, especially in arid areas, appear at depths < 1-1.5m (Figure 2). Together with the effect of the WD, this is also a result of the root zone which is typically located within this range of depth. Marion *et al.*, (2008) modeled salts translocations in Nevada soils and found that about 81% of Ca^{2+} input remained within the top 1m of soils as CaCO_3 . With respect to this, index30 and WDp80 at depths of 0-1m, appear to serve as more accurate proxies as they are not as affected by the boundary limits of the model (compared with some of the MeanWDs). However, these proxies are more sensitive to the variability of the weather series which causes some uncertainty of results even after 5000 years of simulation. It should also be noted that in places with deeper rooting, the evapotranspiration can affect soil beyond the first 1m, in which cases Index30 and WDp80 should be calculated with a modified depth for T.M.Depth in eq.1. MeanWD is less sensitive to T.M.Depth (Table 7). It was also resulted within the top 1.5m of the soil. Therefore, although MeanWD may not be as accurate as Index30 and WDp80, it is more universal and might still be adequate as a gross estimator of the depth to Bk horizons in multiple sites and climates.

6.1.4 Proxies for depth to By horizons

Uncertainty of the proxies for depth to By horizons is greater than for proxies for depth to Bk horizons. Out of the three, MeanSWD simulated better the observed correlation (Figure 18), and it was less sensitive to uncertainty in simulations. This could be an advantage or disadvantage for understanding correlations of weather and depths to By horizons. It is easier to analyze parameters when the results can be repeated easily albeit the stochastic components of the weather generator. However, higher sensitivity might represent actual sensitive behavior of gypsum translocation through the soil profile. As already noted by Marion *et al.*(2008), more than 99% of SO_4 ions were translocated with

only 1% of the water fluxes for their study site in Nevada. This conclusion also supports Index3 as a potential proxy for depth to By horizons. It might present an opportunity to find the correct time scale and weather for scenarios. MeanSWD and SWDp80 are taken from distributions of the seasonal maximal WD and therefore should reflect the combined effects of extremes and frequent rainfalls.

6.2 Effects of weather properties on the Bk horizons proxy and its trends

6.2.1 Variability of weather and the scatter of the results

The results of the global sensitivity simulations (Figure 24) show that variability in weather properties can produce similar scatter of MeanWD with MAR compared to the one found from worldwide observations (Figure 2). This is the same for the other proxies as well, including proxies for depths to By horizons. In general, a weather property's effect is greater when the MAR is higher and the evaporation rate is lower. Therefore, in places with higher MAR, or where PET is lower, the trends are steeper.

Royer (2000) noted that the correlation suggested for the depths to Bk horizons by Retallack (1994) was very much affected by the record of Jenny and Leonard (1934) which include many of the deeper Bk horizons with high MAR. Without using this record, the correlation coefficient R^2 drops from around 0.65 to 0.3. My findings support this claim. Records from places with higher MAR have large effect on the slope of the correlation comparing records from areas that are drier (Figure 20, Figure 22). In Figure 22, I presented local effects of rainfall and PET parameters on the trend with MAR. The difference in rainfall properties had very small effect on the regional trend, and if shifts in climate properties hasn't affected MAR in the studied sites, a regional change in rainfall distribution properties would probably not be detected in the field. Largest effects were calculated for F_d and F_{PET} parameters. However, for areas with higher MAR, the effect on the trend should be greater as can be predicted by the larger effects for MeanWD in Gilat and Be'eri.

6.2.2 Effects of seasonality on trends and correlations of depths to Bk horizons and MAR:

In Figure 24 I present the effect of evaporation on the depths of Bk horizons calculated for 1500 scenarios with various rainfall properties, showing some of the effects of seasonality. The rate of evapotranspiration within the rainy season can cause two results. The first result: shallower MeanWDs with greater scatter in the x axis representing higher

evaporation. This is expected in areas with summer rainfall like in the study site of Jenny and Leonard (1934)). And indeed, the trend of depths to Bk horizons with MAR fits better with this range of results. Or, the second result: deeper MeanWDs with steeper trends and a larger scatter in the y-axis. This is expected in areas with winter rainfall, such as in the study sites of Dan and Yaalon (1982) and in Arkley (1963). The trends reported in these studies are more compatible with the range of results for the lower evaporation factor.

6.2.3 Effects of intra-seasonal rainfall distribution properties on trends and correlations of depths to Bk and MAR:

The rainfall property that most significantly controls depth of MeanWD is the mean event depth (Figure 26.b). However, mean event depth is a product of a combination of various properties whose influences are sometimes hard to separate. The biggest obstacle in evaluating the effect of weather properties on the depths of the proxy is to isolate them. Results of local sensitivity imply the importance of mean event durations, controlled by the Fw parameter, that increase the depth to Bk horizons. Mean daily depth has a slightly lower but similar effect (Figure 21, Appendix VI) that can be controlled by either A or B parameters, i.e. the shape or scale parameters of the daily depth distribution respectively. However, for global data, because of the variety of weather properties and their interactions, the control of daily depths and event durations is not as consistent, obvious and informative as EventsN, especially when depths to Bk horizons are plotted against MAR (Figure 25) or when MAR is kept constant (Figure 26, Figure 27).

Compared with changes in mean daily depth and event durations, when the MAR is controlled only by EventsN, its trend with MAR is very moderate and seem to indicate low sensitivity of MeanWD to EventsN (Figure 23). This is because parameters A, B and Fw were kept constant for these simulations, preserving the mean event depth at similar values. However, if MAR is kept constant, changes in parameter Fd controls EventsN and affects both MAR and MeanWD considerably (Figures 25, 26).

EventsN can be seen as a measure of how MAR is distributed into mean event depths. Therefore, while there are many possible combinations of rainfall properties that can determine various event depths, EventsN can easily simplify trends of depths to Bk horizons and MAR. When plotted against EventsN, the vertical scatter of the results for MeanWD and MAR of 260-310 mm/year, was reduced from about 70 cm (or 12 units of

WHC) to 20cm (or 3.5 units of WHC) (Figures 25- 26). It is controlled by only one parameter of the rainfall generator, i.e.-Fd; it can be obtained from meteorological stations; and it is often discussed in studies that suggest various weather scenarios for past reconstruction or future climate change. Finally, as can be seen in Figure 25, prediction curves of depths to Bk horizons with MAR can be made for various ranges of EventsN. These curves must also be associated with different values for F_{PET} .

Although the results indicate that mean event depths control the Bk depth, an exception exists. When very low daily depths which are smaller than the daily PET reoccur over a long period of time, they can produce high event depths while the mean WD does not increase (Figure 26.c). See the "unaffected results" in Figure 26.b,d and Figure 27.

6.2.4 Interpretations of weather scenarios from depths to Bk horizons: local effects of weather properties on depth to Bk horizons at specific locations

For all examined study sites, the effect of a 20% change in any rainfall parameter causes changes of about 15-50% in depths to Bk horizons and about 15-30% to mean weather properties (EventsN, EventDuration, DailyDepths, extreme daily depth, and frequency of extreme daily depth (Figure 20, Figure 21, Appendix VI)). In areas where the MAR is < 200 mm/year these effects translate to smaller differences than measurement error ($\pm 5\text{cm}$) of depths to Bk horizons (Figure 20, Figure 22).

My results suggest that in an area where rainfall is < 200mm/year there will be no considerable differences in depths to Bk horizons even for local changes of 20% of climate parameters.

Some (Enzel,1984; Magaritz,1986; Goodfriend and Magaritz, 1988) have interpreted Bk horizons found in the central Negev as indicators of the Pleistocene-Holocene climate change in the region. This attempt was not preceded and entails further research. What can be suggested by my findings is that if a measurable difference between Bk horizons of Pleistocene and Holocene ages was found south to Beer-Sheva, the difference in weather properties between the ages must have been larger than 20% for any one of the properties mentioned here, or made of a combination of weather properties. For example, if evaporation was the only property to shift, with no change to MAR, as suggested by Bar-Matthews *et al.*(2003), a higher change than 20% to F_{PET} was necessary. 50% decrease could be significant even for MAR in the range of 100-200mm (Figure 22).

Enzel *et al.* (2008) suggested a higher frequency of events per year and greater events depths. Judging from the moderate effect of F_d on the trend of MeanWD with MAR (Figure 23), an increase in EventsN will not be as important as increase in F_w , A or B (Figure 20), unless MAR in Pleistocene time was similar to present (Figure 22). The interaction of the variables could be significant and should be tested against more specific scenarios or known differences in depth to Bk horizons between Holocene and late Pleistocene soils. A combination of moderate increases in rainfall properties together with some reduction in PET would probably result with significant deepening of the MeanWD.

Similarly, some conclusions can be made for climate change scenarios. Knapp *et al.* (2015) noted that some climate change models predict an increase in frequencies and depths of extreme events in semi-arid areas. The increase is predicted to be ~15%. According to the simulations in this study, and the association of Bk horizons and the soil's WetZone, I suggest that the effect of this amount of change in rainfall properties on the WDs and the ecological system would be very small in arid and semi-arid areas with MAR <200 mm, and would probably be more observable in wetter areas. Low evaporation rates would shift this boundary to lower rainfalls.

It is important to note here again that the simulations in the Negev, given in centimeters were calculated for soils with $WHC=0.17 \text{ cm}^3/\text{cm}^3$. Smaller WHC, for example, in sandier soils, might emphasize the effects of the weather in areas with lower MAR.

While there may be some small differences in the calculated depths of the Bk horizons, all that is said about the behavior of MeanWD regarding changes in weather properties is also applicable to Index30 and WDp80.

6.3 Steps required for further refinement of the model and analysis

6.3.1 Limitations of the analysis

The rainfall generator here applies a single pick Gaussian describing the probability of having rainfall episodes during an entire season. Having periods of synoptic conditions leading to more than one peak of the rainfall distribution along the season, would increase the variance of length of dry spells between rainfall events and the effects of the mean event depths would not be as simple as in the analysis presented by Figure 26.b. In such cases, the mean event depths of some synoptic conditions may be more important than others and their effects must be viewed separately. For this to be tested, some more

parameters should be added to the analysis: factors over the width of the WAW and WAD probability Gaussians will control the length of each period; and for the simulations to be done separately, mean initial water content of the profile should be added at the beginning of each year of simulation. With this, Gaussians widths and heights, the daily depth distributions (scale and shape parameters) and the mean soil water content in the beginning of the periods will control the simulations. That would allow more complex scenarios that could simulate effects of extreme events separately from the means. The scale parameter (B) for the daily depth distributions was neglected from the global sensitivity analysis and it should be tested.

This study is the first to suggest a modeling framework for studying the effects of weather properties on the long term soil water dynamics. Therefore, it was important to first show feasibility of the model for this kind of investigation, and to describe the effects of simpler and smaller set of mean rainfall properties. Another parameter that was neglected from the analysis for the same reasons is the width of the PWA and PWAD Gaussians, which would result with different lengths for the rainfall season. While F_d and F_w control the height of the Gaussians thus affecting the number and durations of events, the effect of season's length on these properties was not tested.

The global sensitivity was done by changing the weather parameters in fixed intervals. This limits the amount and variability of the scenarios that were available for the analysis. A more adequate way of doing that would be with random choice of parameters using Monte-Carlo procedure. In this research, this was not done because of computing time considerations, however once the model and Bk horizons proxies were validated to some extent, it should not be difficult to write a more efficient code that would calculate the scenarios much faster and allow for more parameters to be tested.

Many studies note the importance of quantifying the effect of dry spells on soil water (e.g. Marion and Schlesinger, 1994; Marion *et al.*, 2008; Knapp *et al.*, 2015). As long as daily depths are larger than daily evaporation, total event depth and pre-existing water content in soil profile will determine the WD. The pre-existing water content in soil profile can be reduced by high PETs and by long dry spells, and this is why the results are shallower for high PET and summer rainfall. For moderate PET, the effect of the mean dry spell is not as significant. The mean property hinders many possible combinations of dry spells, some

will contribute to a decrease or increase in MeanWD – the effects of which are moderated by the mean. Therefore, analysis of this property requires simulations of specific scenarios that would be created in order to answer specific questions.

6.3.2 Calibrated parameters in Gilat and assumptions made for simulations in other sites

Soil texture analyses of samples from Gilat and Sde-Boker suggest that the spatial variability in texture is small within the Negev loessial soils. Therefore, although the parameters were calibrated only with Gilat data series, the results should be appropriate for the entire study site. Yet, differences in vegetation and relative humidity also affect parameters related to the evaporation procedure such as K_c , T.M.Depth and WHCIndex. Currently there is limited information from the monitoring stations to explore effects of these differences and I have made several concessions due to insufficient information or time, which should be discussed.

The calibration of K_c and WHC is based on two rainfall events that occurred in proximity to the time when the monitoring station in Gilat was installed. On the one hand, soil water monitoring data is usually thought to be reliable only after the soil had a complete cycle of wetting and drying. On the other hand: measures were taken to make sure that the sensors represented water content data from undisturbed soil; the calibration procedure predicted similar values for FC as the pedotransfer function of the Rosetta software. Soil parameters also seemed to be validated by simulations with Hydrus 1D which are not presented here.

The PET generator did not produce sufficient variance of the results and the model should be refined. Beyond Gilat, it was not adapted to other sites due to insufficient PET data. The rainfall generator predicted accurate rainfall mean properties and standard deviations of mean properties for Gilat and other locations (Appendix V). Gaussians of PWA_W and PWA_D were derived for measured rainfalls in Be'eri, Be'er-Sheva and Sde-Boker and were found to be very similar to Gilat, therefore using the same Gaussians with slight changes was justified. However, some discrepancies were found in the simulations of other sites for wetter and dryer years (Figure 15) and for frequencies of extreme daily depths (Appendix V). These may have affected the results. In this regard, MeanWD is the more appropriate proxy for depths to B_k because, as explained earlier, it is less sensitive

to extremes than to mean weather properties and may be less affected by these discrepancies.

Overall, the results of this study provide good approximations to field data and some insights can be learned towards quantifications of weather properties on the long-term effects of soil water dynamics, and possibly on its effects on depths to Bk and By horizons. Most importantly, the framework suggested here can be tested and refined further to be applied to other processes that are related to long-term soil water dynamics.

7 Conclusions

Previous efforts to associate depths of Bk and By horizons with climate were either based on empirical correlations with M, disregarding the effects of other weather properties, or based on modeling weather and translocations of ions in the soil which had to be very site specific. Uncertainty issues limit both of these approaches to small regions with similar environments. The compartment model along with the weather generator built in this study, make it possible to associate long term soil water dynamics with depths to Bk and By horizons, and therefore, to study and measure the effects of various weather properties on the depths of the horizons. Although the models were built and calibrated for a study site in northern Negev, Israel, it could also be accommodated to other sites. The results presented here can be given in terms of WHC units, which can be translated into length units for any soil with no need of additional simulations, making it universal. The long term soil water here was simplified into distributions of the soils' wetting depths (WDs) and water fluxes, from which the MeanWD, WDp80 and Index30 were associated with depths to Bk horizons in the study site, suggesting them as proxies for the depths of Bk horizons. The universality of these variables as proxies for the depths to Bk horizons should be tested against empirical data with weather scenarios of other sites.

The main findings of this study are:

1. Variability in weather properties, other than MAR, can be the cause of the great scatter in worldwide observations of depths to Bk and By horizons plotted against the MAR.
2. Differences between trends of areas with different rainfall seasonality can be explained by differences in evaporation rates during the rainfall season.
3. Contrary to prevailing opinions, shallower Bk horizons can develop in areas with similar or lower MAR if PET rates or annual number of events are higher (events depths are lower).
4. Events depths and the mean daily PET (within the rainfall season) are the most important factors that control the depth to Bk and By soil horizons.

5. In this model, F_d , which control the mean number of events per year and F_{PET} , which control the mean daily PET (within the rainfall season) are the most effective parameters for resulted trends between soil horizons' proxies and MAR.
6. Universal trends of depth to Bk horizons with the MAR can be made for ranges of mean daily PET and mean number of events per year.
7. The effect of any weather property increases with increase in MAR and with decrease in mean daily PET. The same can be said for steepness of trends of depths to Bk horizons with the MAR.
8. According to the local sensitivity, 20% change in the weather parameters, which translates 15-30% changes in the mean weather properties cannot be detected by depth to Bk horizons in areas with $MAR < 200$ mm/year. Therefore past or future changes in climate would have to be larger than 20% for any single parameter, or result from a combination of changed properties to create recognizable impact to soil water dynamics in these regions.
9. In areas with lower PET (at rainfall season) or smaller WHC, this boundary will shift to lower MAR than 200 mm/year.
10. The effect of any weather property grows with decrees in the soils' WHC.

The framework suggested here allows quantification for the effects of weather on wetting depths and Bk, and By proxies. With this it is possible to: (1) further the study of universal soil forming functions; (2) conduct weather scenarios for specific paleo-climate and future-climate questions.

A good next step would be to try and retrieve universal correlations and suggest predictive curves of depths to Bk and MAR from global record for different ranges of mean daily PET and mean events per year. These could then be tested against empirical data.

8 References

- Amit, R., Enzel, Y., & Sharon, D. (2006). Permanent Quaternary hyperaridity in the Negev, Israel, resulting from regional tectonics blocking Mediterranean frontal systems. *Geology*, 34(6), 509-512.
- Amit, R., Enzel, Y., Grodek, T., Crouvi, O., Porat, N., & Ayalon, A. (2010). The role of rare rainstorms in the formation of calcic soil horizons on alluvial surfaces in extreme deserts. *Quaternary Research*, 74(2), 177-187.
- Arkley, R. J. (1963). Calculation of carbonate and water movement in soil from climatic data. *Soil Science*, 96(4), 239-248.
- Assouline, S., & Or, D. (2014). The concept of field capacity revisited: Defining intrinsic static and dynamic criteria for soil internal drainage dynamics. *Water Resources Research*, 50(6), 4787-4802.
- Avni, Y., Porat, N., & Avni, G. (2012). Pre-farming environment and OSL chronology in the Negev Highlands, Israel. *Journal of arid environments*, 86, 12-27.
- Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., Hawkesworth, C.J., 2003. Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implications for paleorainfall during interglacial intervals. *Geochimica et Cosmochimica Acta* 67, 3181-3199.
- Bar-Matthews, M., Ayalon, A., Kaufman, A., 1997. Late Quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research* 47, 155-168
- Ben-Zvi, A. (1996). Quantitative prediction of runoff events in the Negev desert. In *Runoff, Infiltration and Subsurface Flow of Water in Arid and Semi-Arid Regions* (pp. 121-130). Springer Netherlands.
- Birkland, P.W., (1984), *Soils and Geomorphology*, Oxford Univ. Press, New York.
- Breecker, D. O., Z. D. Sharp, and L. D. McFadden. 2009. "Seasonal Bias in the Formation and Stable Isotopic Composition of Pedogenic Carbonate in Modern Soils from Central New Mexico, USA." *Bulletin of the Geological Society of America* 121(3-4): 630-40.
- Brocca, L., Melone, F., & Moramarco, T. (2008). On the estimation of antecedent wetness conditions in rainfall-runoff modelling. *Hydrological Processes*, 22(5), 629-642.
- Coe, R., & Stern, R. D. (1982). Fitting models to daily rainfall data. *Journal of Applied Meteorology*, 21(7), 1024-1031.
- Cohen, A. S. (1982). Paleoenvironments of root casts from the Koobi Fora Formation, Kenya. *Journal of Sedimentary Research*, 52(2), 401-414.
- Crouvi, O., Amit, R., Enzel, Y., Porat, N., Sandler, A., 2008. Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev Desert, Israel. *Quaternary Research* 70, 275-282.
- Dan, J., & Yaalon, D. H. (1982). Automorphic saline soils in Israel. In *Acidic soils and geomorphic processes: proceedings of the International Conference of the International Society of Soil Science*, Jerusalem, Israel, March 19-April 4, 1981/DH Yaalon, ed. Cremlingen [W. Ger.]: Catena Verlag, 1982..
- Dunkerley, D. (2017). An approach to analysing plot scale infiltration and runoff responses to rainfall of fluctuating intensity. *Hydrological Processes*, 31(1), 191-206.
- Dunkerley, D. (2012). Effects of rainfall intensity fluctuations on infiltration and runoff: rainfall simulation on dryland soils, Fowlers Gap, Australia. *Hydrological Processes*, 26(15), 2211-2224.

Dunn, P. K. (2004). Occurrence and quantity of precipitation can be modelled simultaneously. *International Journal of Climatology*, 24(10), 1231-1239.

Eisenberg, J., 1980. The effects of parent material, exposure and relief on soil and vegetation characteristics in the Beeri badlands of the northern Negev, *Geography*. University of Tel-Aviv, Tel-Aviv, p. 147

Enzel, Y., (1984). The geomorphology of the lower Wadi Secker. Jeru- salem, Israel, M.Sc. thesis, The Hebrew University of Jerusalem, 102 p. In Hebrew with English abstract

Enzel, Y., Amit, R., Dayan, U., Crouvi, O., Kahana, R., Ziv, B., & Sharon, D. (2008). The climatic and physiographic controls of the eastern Mediterranean over the late Pleistocene climates in the southern Levant and its neighboring deserts. *Global and Planetary Change*, 60(3-4), 165-192.

Gerson, R., & Amit, R. (1987). Rates and modes of dust accretion and deposition in an arid region—the Negev, Israel. *Geological Society, London, Special Publications*, 35(1), 157-169.—the Negev, Israel. *Geological Society, London, Special Publications*, 35(1), 157-169.

Gile, L.H., Hawley, J.W., Grossman, R.B., 1981. Soils and Geomorphol- ogy in the Basin and Range area of Southern New Mexico— Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222pp

Goodfriend, G.A., & Magaritz, M., (1988). Paleosols and late Pleistocene rainfall fluctuations in the Negev Desert. *Nature* 322, 144–146

Hirmas, D. R. (2008). Surface processes, pedology, and soil-landscape modeling of the southern Fry Mountain bolson, Mojave Desert, California. University of California, Riverside.

Howell, T. A., & Evett, S. R. (2004). The Penman-Monteith Method. USDA-Agricultural Research Service Conservation & Production Research Laboratory: Bushland, TX, USA.

IMS report (2011): <http://www.ims.gov.il/IMS/CLIMATE/ClimaticAtlas/RainMaps.htm>

Jenny, H. (1941). Factors of soil formation. McGraw-Hill, New York. Factors of soil formation. McGraw-Hill, New York.

Jenny, H., & Leonard, C. D. (1934). Jenny, H., & Leonard, C. D. (1934). Functional relationships between soil properties and rainfall. *Soil Science*, 38(5), 363-382.. *Soil Science*, 38(5), 363-382.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A. and Wilby, R.L., (2007). A daily weather generator for use in climate change studies. *Environmental Modelling & Software*, 22(12), 1705-1719.

Knapp, A. K., Beier, C., Briske, D. D., Classen, A. T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A. and Heisler, J.L., (2008). Consequences of more extreme precipitation regimes for terrestrial ecosystems. *AIBS Bulletin*, 58(9), 811-821.

Knapp, A. K., Hoover, D. L., Wilcox, K. R., Avolio, M. L., Koerner, S. E., La Pierre, K. J., ... & Smith, M. D. (2015). Characterizing differences in precipitation regimes of extreme wet and dry years: implications for climate change experiments. *Global change biology*, 21(7), 2624-2633.

Laio, F. (2006). A vertically extended stochastic model of soil moisture in the root zone. *Water resources research*, 42(2).

Li, P., Li, T., & Vanapalli, S. K. (2016). Influence of environmental factors on the wetting front depth: A case study in the Loess Plateau. *Engineering Geology*, 214, 1-10.

Magaritz, M., 1986. Environmental changes records in the Upper Pleistocene along the desert boundary, southern Israel. *Palaeogeo- graphy, Palaeoclimatology, Palaeoecology* 53, 9–16.

- Marion, G. M. (1994). CALGYP: A Simulation Model for Calcite and Gypsum Precipitation-Dissolution in Soils (No. CRREL-SR-94-19). COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH.
- Marion, G. M., & Schlesinger, W. H. (1994). Quantitative modeling of soil forming processes in deserts: The CALDEP and CALGYP models. *Quantitative Modeling of Soil Forming Processes, (quantitativemod)*, 129-145.
- Marion, G. M., P. S.J. Verburg, E. V. McDonald, and J. A. Arnone. 2008. "Modeling Salt Movement through a Mojave Desert Soil." *Journal of Arid Environments* 72(6): 1012–33.
- Marion, G. M., Schlesinger, W. H., & Fonteyn, P. J. (1985). CALDEP: A regional model for soil CaCO₃ (caliche) deposition in southwestern deserts. *Soil Science*, 139(5), 468.
- Mayer, L., (1988)., Distribution of calcium carbonate in desert soils: a computer simulation using program CALSOIL, US Geological Survey Open-File Report 86-155,36 p.
- Mayer, L., L.D. McFadden, and J.W. Harden. 1988. Distribution of calcium carbonate in desert soils: A model. *Geology* 16:303–306. doi:10.1130/0091-7613(1988)016<0303:DOCCID>2.3.CO;2
- Mayer, L., McFadden, L. D., Harden, J. W., Taylor, E. T., Reheis, M. C., & Arkley, R. (1985). Computer simulation of calcic soil development for paleoclimatic reconstructions using an iterative forward method structured on the compartment model. *Geol. Soc. Am., Abstr. Programs;(United States)*, 17(CONF-8510489-).
- McDonald, E.V., F.B. Pierson, G.N. Flerchinger, and L.D. McFadden. 1996. Application of a soil-water balance model to evaluate the influence of Holocene climate change on calcic soils, Mojave Desert, CA. *Geoderma* 74:167–192
- McFadden, L. D. (1982). THE IMPACTS OF TEMPORAL AND SPATIAL CLIMATIC CHANGES ON ALLUVIAL SOILS GENESIS IN SOUTHERN CALIFORNIA.
- McFadden, L. D., & Tinsley, J. C. (1985). Rate and depth of pedogenic-carbonate accumulation in soils: Formulation and testing of a compartment model. *Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper*, 203, 23-41.
- Meyer, N. A. (2012). Simulating the accumulation of calcite in soils using the soil hydraulic model HYDRUS-1D (Doctoral dissertation).
- Meyer, N. A., Breecker, D. O., Young, M. H., & Litvak, M. E. (2014). Simulating the effect of vegetation in formation of pedogenic carbonate. *Soil Science Society of America Journal*, 78(3), 914-924.
- Morin E., Marra F. and Armon M. (2019) Dryland Precipitation Climatology from Satellite Observations. In: Levizzani, V., Kidd, C., Kirschbaum, D., Kummerow, C., Kummerov, K., and TurkF. J. (Editors) *Satellite .Precipitation Measurement*, Springer
- Mualem, Y. (1976). catalogue of the hydraulic properties of unsaturated soils.
- Pan, F., Peters-Lidard, C. D., & Sale, M. J. (2003). An analytical method for predicting surface soil moisture from rainfall observations. *Water Resources Research*, 39(11).
- Papadakis, J. (1965). Potential evapotranspiration: Some considerations on Penman method. A simpler and more accurate formula "Stomatic" evaporimeter: Buenos Aires, Argentina, 54 p.
- Piedallu, C., Gégout, J. C., Perez, V., & Lebourgeois, F. (2013). Soil water balance performs better than climatic water variables in tree species distribution modelling. *Global Ecology and Biogeography*, 22(4), 470-482.
- Retallack, G. J. (1994). The environmental factor approach to the interpretation of paleosols. *SSSA Special Publication*, 33, 31-31.

Retallack, G. J. (2000). Depth to pedogenic carbonate horizon as a paleoprecipitation indicator?. *indicator*, 27, 1123-1126.

Retallack, G. J. (2005). Pedogenic carbonate proxies for amount and seasonality of precipitation in paleosols. *Geology*, 33(4), 333-336.

Retallack, G. J., & Huang, C. (2010). Depth to gypsic horizon as a proxy for paleoprecipitation in paleosols of sedimentary environments. *Geology*, 38(5), 403-406.

Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. *Physics*, 1(5), 318-333.

Richardson, C. W. (1981). Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water resources research*, 17(1), 182-190.

Robinson, S. A., Black, S., Sellwood, B. W., & Valdes, P. J. (2006). A review of palaeoclimates and palaeoenvironments in the Levant and Eastern Mediterranean from 25,000 to 5000 years BP: setting the environmental background for the evolution of human civilisation. *Quaternary Science Reviews*, 25(13), 1517-1541.

Rohling, E. J., Grant, K. M., Roberts, A. P., & Larrasoña, J. C. (2013). Paleoclimate variability in the Mediterranean and Red Sea regions during the last 500,000 years: implications for hominin migrations. *Current Anthropology*, 54(S8), S183-S201.

Royer, D. L. (2000). Depth to pedogenic carbonate horizon as a paleoprecipitation indicator?: Comment and Reply: REPLY. *Geology*, 28(6), 572-572.

Schaap, M. G., Leij, F. J., & Van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of hydrology*, 251(3-4), 163-176.

Schaetzl, R. J., & Anderson, S. (2006). Soils: Genesis and Geomorphology Reviewed by Joseph A. Mason. *Annals of the Association of American Geographers*, 96(4), 827-828.

Schlesinger, W. H. (1985). The formation of caliche in soils of the Mojave Desert, California. *Geochimica et Cosmochimica Acta*, 49(1), 57-66.

Semenov, M. A., & Brooks, R. J. (1999). Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. *Climate Research*, 11(2), 137-148.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J., (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3), 125-161

Simunek, J., Van Genuchten, M. T., & Sejna, M. (2005). The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. *University of California-Riverside Research Reports*, 3, 1-240.

Smith, K. (1965). A long-period assessment of the Penman and Thornthwaite potential evapotranspiration formulae. *Journal of Hydrology*, 2(4), 277-290.

Tabor, N. J., & Myers, T. S. (2015). Paleosols as indicators of paleoenvironment and paleoclimate. *Annual Review of Earth and Planetary Sciences*, 43, 333-361.

The National Atlas, (2008) : The New Atlas of Israel, ISBN:978-965-91256-0-9, Tel Aviv-Jaffa, Jerusalem.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical review*, 38(1), 55-94.

Tsakiris, G. (1988). Daily potential evapotranspiration modelling. *Agricultural water management*, 13(2-4), 393-402.

Tu, X. B., Kwong, A. K. L., Dai, F. C., Tham, L. G., & Min, H. (2009). Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. *Engineering Geology*, 105(1), 134-150.

Vaks, A., Bar-Matthews, M., Ayalon, A., Matthews, A., Frumkin, A., Dayan, U., Halicz, L., Almogi-Labin, A., Schilman, B., 2006. Paleoclimate and location of the border between Mediterranean climate region and the Saharo-Arabian Desert as revealed by speleothems from the northern Negev Desert, Israel. *Earth and Planetary Science Letters* 249, 384–399. corrected!

Wang, T. (2014). Modeling the impacts of soil hydraulic properties on temporal stability of soil moisture under a semi-arid climate. *Journal of hydrology*, 519, 1214-1224.

Wang, X. P., Cui, Y., Pan, Y. X., Li, X. R., Yu, Z., & Young, M. H. (2008). Effects of rainfall characteristics on infiltration and redistribution patterns in revegetation-stabilized desert ecosystems. *Journal of Hydrology*, 358(1), 134-143.

Wilks, D. S., & Wilby, R. L. (1999). The weather generation game: a review of stochastic weather models. *Progress in physical geography*, 23(3), 329-357.

Yaalon, D. H., & Dan, J. (1974). Accumulation and distribution of loess-derived deposits in the semi-desert and desert fringe areas of Israel. *Z. Geomorphol. Suppl*, 20, 91-105.

Zamanian, K., Pustovoytov, K., & Kuzyakov, Y. (2016). Pedogenic carbonates: Forms and formation processes. *Earth-Science Reviews*, 157, 1-17.

Ziv, B., Dayan, U., Kushnir, Y., Roth, C., Enzel, Y., 2006. Regional and global atmospheric patterns governing rainfall in the southern Levant. *International Journal of Climatology* 26, 55–73. Added!

Ziv, B., Saaroni, H., Pargament, R., Harpaz, T., & Alpert, P. (2014). Trends in rainfall regime over Israel, 1975–2010, and their relationship to large-scale variability. *Regional environmental change*, 14(5), 1751-1764.

Appendix I – List of definitions and variables

List of variables and symbols

WDs	wetting depths- a conceptual term describing the distribution of depths of soil wettings by rainfalls. See also WD in Model Loggers further down this list.
MAR	mean annual rainfall (mm/year)

Soil Horizons

Bk	illuvial soil horizon in with secondary carbonate precipitated to form carbonate nodules (American Soil Science nomenclature)
By	illuvial soil horizon in which secondary gypsum was precipitated (American Soil Science nomenclature)

Water Contents in soils- conceptual definitions

FC	maximal water holding capacity of the soil against gravity (cm^3/cm^3)
WP	minimal water holding capacity of the soil against transpiration (cm^3/cm^3)
θ_r	minimal water holding capacity of the soil against evaporation (cm^3/cm^3)
WHC	the difference between maximal and minimal available soil water contents - usually: $\text{FC} - \theta_r$ (cm^3/cm^3)

Evapo-Transpiration

PET	the potential evapo-transpiration (mm/day), is depended only in the atmospheric energy demand.
AET	actual evapo-transpiration (mm/day), is depended in PET and in the available water content of the soil profile
Kc	Crop coefficient (unit-less): conceptual and semi-empiric assessment of vegetation effect that limit evapo-transpiration rates.

Prescribed parameters for the AET procedure in the compartment model (Eq.1)

T.M.Depth	Effective soil depth for evapotranspiration processes. Ratio of the total moisture in the soil profile to the WHC of the profile is taken at depth range of 0-T.M.Depth to determine the daily AET according to WHCIndex In this study it was assumed as the top 1m of the soil.
WHCIndex	Ratio of the mean soils' WHC range that determines transition from an AET which is controlled by the atmospheric demanded ($\text{AET} = \text{Kc} * \text{PET}$) or an AET that is controlled by the available soil water content (decreases with TotalMoisture). This is an empirical parameter that was retrieved from field measurements in California. It was taken at 0.546 according to Marion et al. (1985).

Model Loggers of soils' long-term water dynamics

WD	wetting depth (cm) is the maximal depth of water income to the soil after rain - logged as a daily depth.
WaterFluxOut	amount of water that proceeds downward flow from each compartment - logged as an array of cumulative water contents (cm ³ /cm ³) for each compartment
WetZone	cumulative days in which a compartment is filled to its maximal capacity of FC water content (days) - logged as an array

WD and flux Proxies for depths to Bk and By

MeanWD	average depth of daily wetting depth (cm) - indicates depth to Bk
SMeanWD	average depth of the maximal wetting depths per season (cm) - indicates depth to By
WDp80	80th percentile of daily wetting depths (cm) - indicates depth to Bk
SWDp80	80th percentile of the maximal wetting depths per season (cm) - indicates depth to By
Index30	soil depth at which WaterFluxOut =30% of the total simulated rainfall (cm) - indicates depth to Bk
Index3	soil depth at which WaterFluxOut =30% of the total simulated rainfall (cm) - indicates depth to By

Weather generator definitions day types and distributions

Wet Day	day with rain depth of 0.1 mm or more.
Dry day	day with no rain or up to the lower limit of measured depth of 0.1 mm
WAW day	wet after wet day - a day within rainfall event. In the rainfall generator - WAW was assigned with probability of occurrence according to the day in the year; in the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
WAD day	wet after dry day - the first day in a rainfall event of one day or longer. WAW was assigned with probability of occurrence according to the day in the year; in the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
DAW day	dry after wet day - the first day after a rain event stopped (first in a dry spell). In the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
DAD day	dry after dry day - a day within a dry spell. In the PET generator, WAW was assigned with distribution of deviations of the daily PET from the monthly mean.
PWAD	probability of a WAD day occurring for each day of 365 day's year - representing probability for starting a rain event according to the time in the year. Empirical data was fitted with a Gaussian.
PWAW	probability of a WAW day occurring for each day of 365 day's year - representing probability for continuing of a rain event according to the time in the year. Empirical data was fitted with a Gaussian.

Input parameters that control weather properties

Fd	input parameter to the rainfall generator controlling frequency of events per year: a factor over PWAD Gaussian
Fw	input parameter to the rainfall generator controlling duration of events: a factor over PWAW Gaussian
A	input parameter to the rainfall generator, mostly controlling the mean daily depth. this is the scale parameter of the daily depth Weibull distribution function (mm)
B	Input parameter to the rainfall generator, mostly controlling the extreme daily depth. This is the shape parameter of the daily depth Weibull distribution function (--)
F_{PET}	input parameter to the compartment model in order to simulate higher/lower PET or Kc. This is a factor over the daily PET time-series.

Rainfall distribution properties (intra-annual)

EventsN	mean frequency of events* (events/year): calculated from a distribution of annual number of events.
EventsDurations	mean event* duration (days/event): calculated from a distribution of all event durations in the record or simulation.
EventsDepth	mean event* depth (mm/event): calculated from a distribution of all event durations in the record or simulation.
DailyDepth	mean daily depth (mm) - calculated from a distribution of all daily depths (not an annual mean) in the record or simulation.

* a rainfall event is defined as 1 or more consecutive days with daily rainfalls > 0.1mm

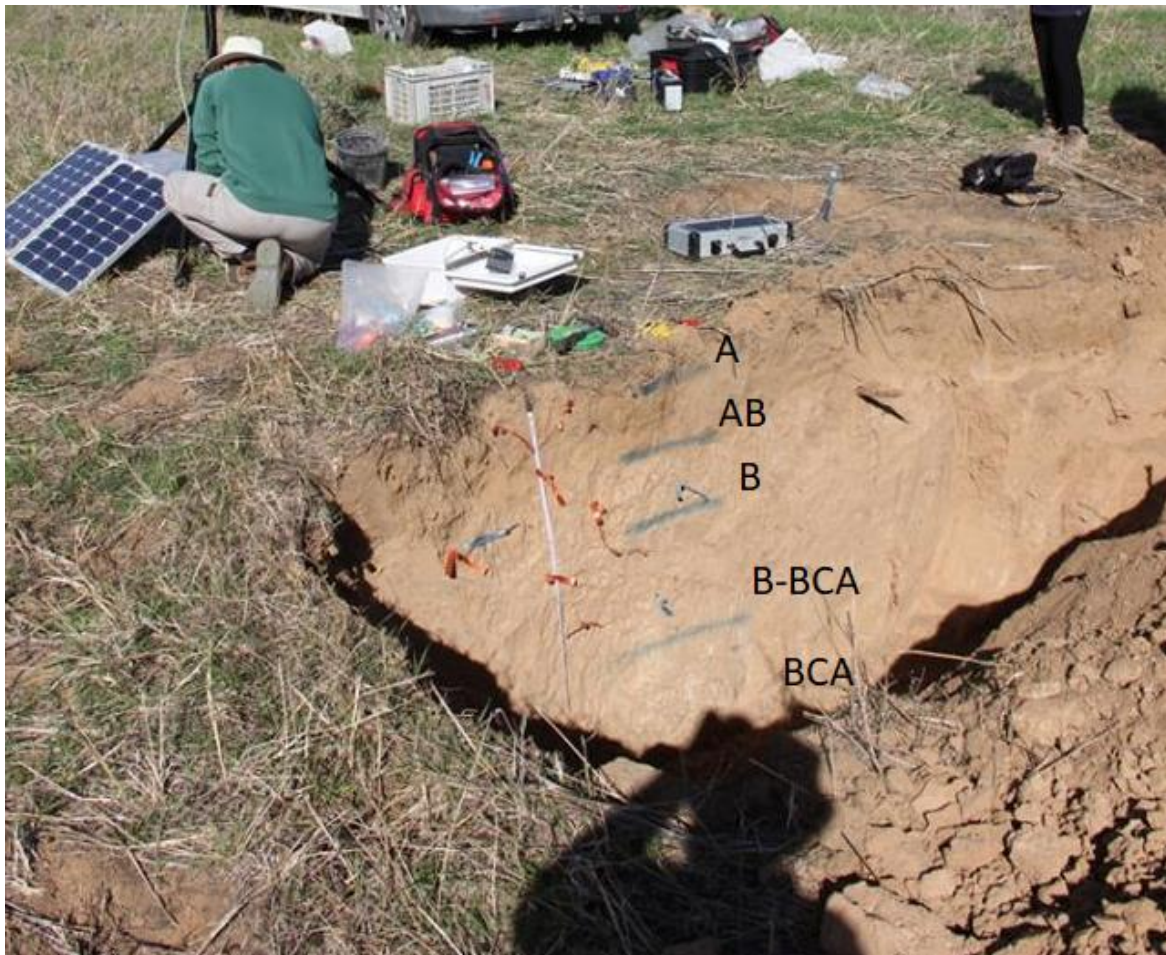
Appendix II- Description of the soil profile of 'Gilat' monitoring station

Gilat profile - Monitoring sensors and soil samples

Depth (cm)	Horizon	Field description	TDR sensors *	Soil samples: Name [GSI-ID]	Mid. Sample depth (cm)**	Dry color (Munsell)
0-10	A	Rich in rootlings + some organic material, loose and dark	10R, 10L	24GILAT [2768] 04GILAT [2861]	10 20	7.5YR-5/4 brown 7.5YR-5/4 brown
10-30	AB	Rich in rootlings - depth of illuviation	27R	23GILAT [2767] 07GILAT [2764]	27 40	7.5YR-5/4 brown 7.5YR-6/4 light brown
30-55	B	Shift to lighter color, almost no roots	45R, 45L	16GILAT [2766]	40	
			60L	18GILAT [2765]	60	7.5YR-6/4 light brown
55-100	B-BCA	Beginning of small carbonate concentrations - size and density grows especially at 90 cm	80R	08GILAT [2862] 17GILAT [2769]	80 90	10YR-7/4 very pale brown 7.5YR-5/4 brown
				09GILAT [2863]	110	10YR-7/4 very pale brown
100-140	BCA	Illuvial horizon - reach with calcium carbonate		21GILAT [2770]	130	10YR-6/4 light yellowish brown

* Sensors names were numbered by depths in cm

** Sampled with in-situ soil sampler (100ml cups, 5cm diameter)



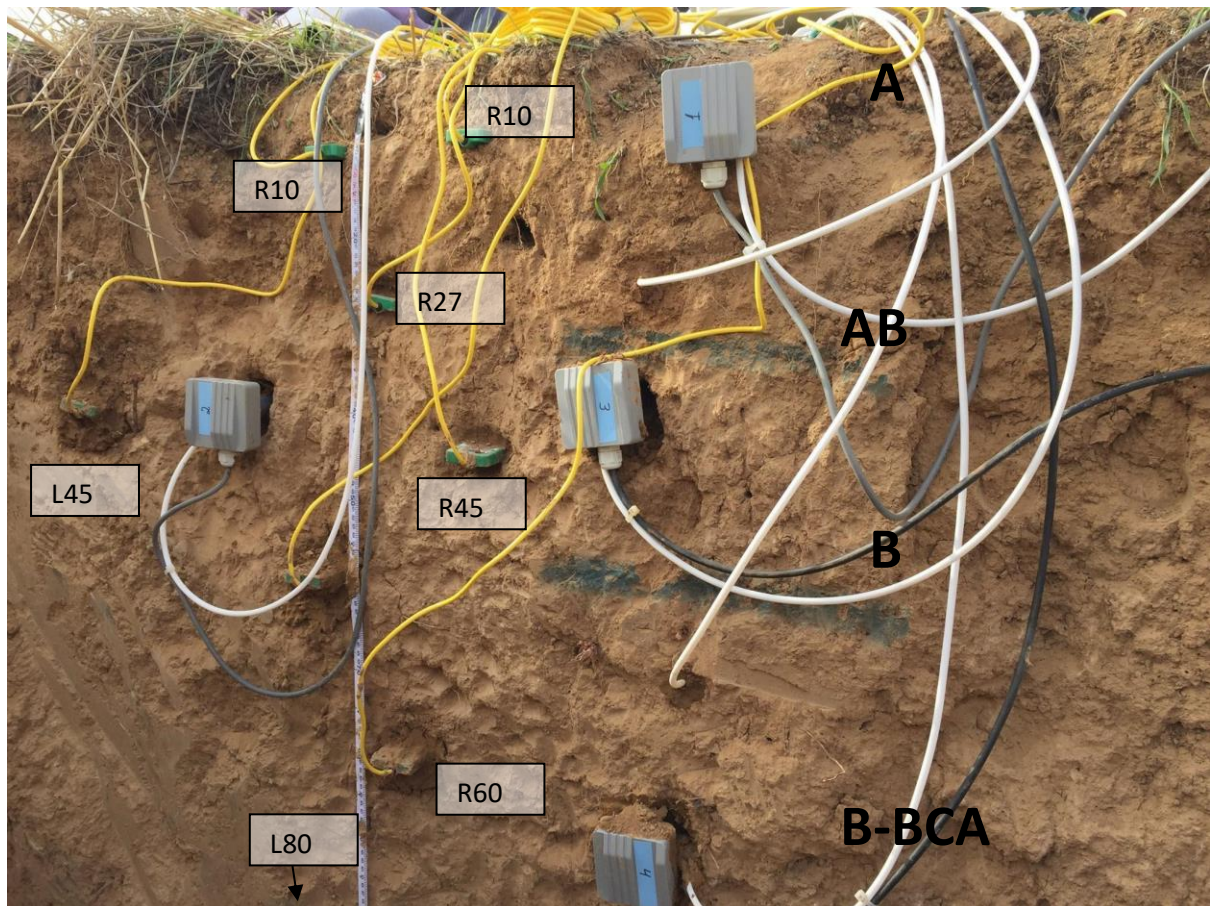
Appendix ii-1 Soil profile of Gilat monitoring station previous to sensors installation – red ribbons mark the position of TDR sensors; blue ribbons mark the position of CO₂ sensors (not discussed in this study). Picture take at the day of installation: winter time, 05.01.17.



Appendix ii-2 Monitoring station in Gilat: sensors installed into the undisturbed trench wall. Mud inserted the TDR .sensors for continuity of soil. Than the trench was covered. Grassy surface



Appendix ii-3 on the left: TDR installation with mud filling the space around the sensor. On the right: the in-situ soil .sampler



Appendix ii-4 TDR and CO₂ sensors in the monitoring station in Gilat.

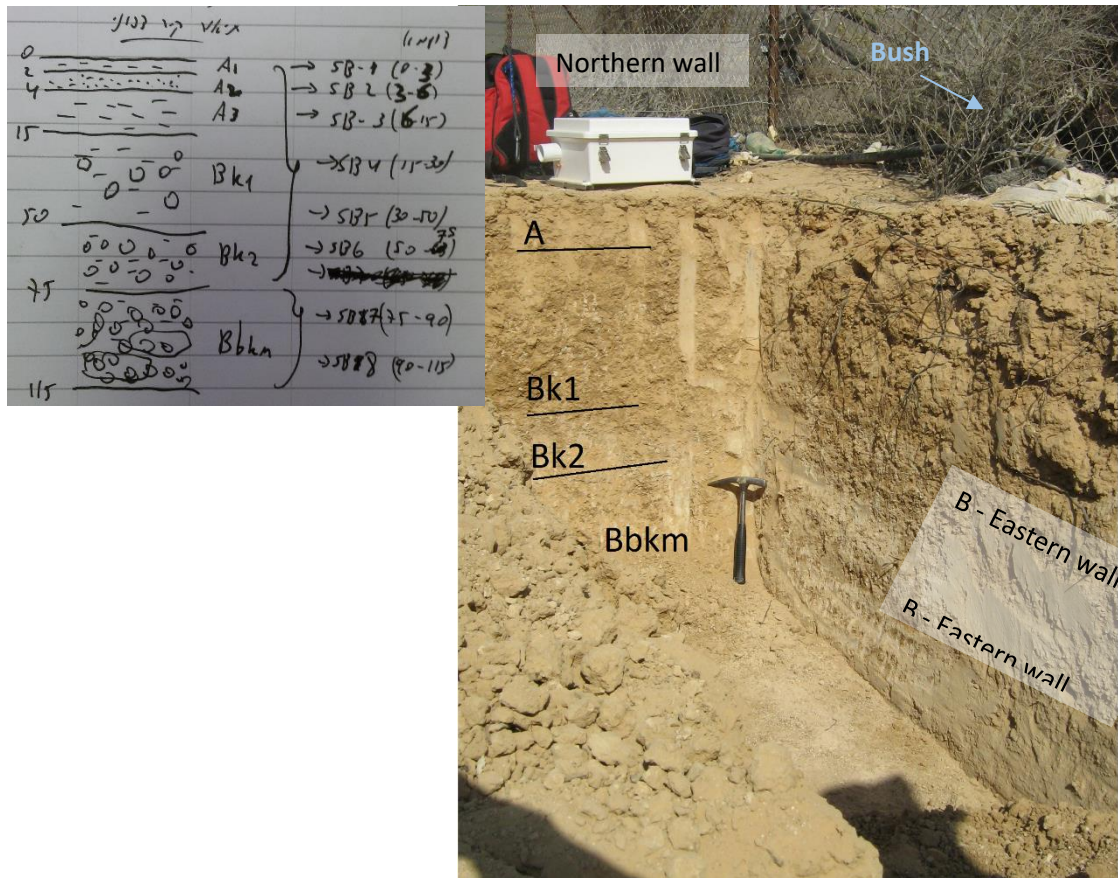
Appendix III- Description of the soil profile of 'Sde Boker' monitoring station

Sde Boker profile - Monitoring sensors and soil samples

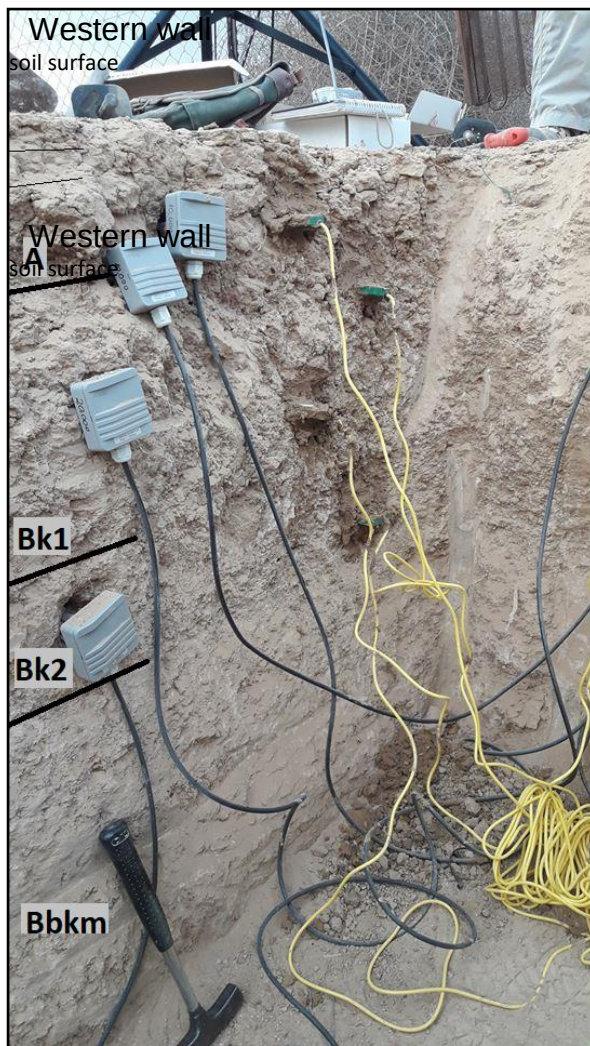
Depth (cm)	Horizon	Field description	TDR sensors *	Soil samples: Name [GSI-ID]	Sample depth (cm)	Dry color (Munsell)
0-15	A	Loess with lots of rootlings and reddish sandy unit: A1 0-3 cm layered loessial crust with rootlings, no carbonates A2 3-6 cm Reddish sand, unclear if antropogenic, layered A3 6-15 cm Massive loess, lots of rootlings	10A,10B	SB-1 [2769]	0-3	10YR-7/4 very pale brown
				SB-2 [2770]	3-6	7.5YR-6/6 reddish yellow
				SB-3 [2771]	6-15	10YR-7/4 very pale brown
15-50	Bk1	B horizon with about 25% cover of carbonate concentrations, 12cm size, difusive, column structure	25A,25B 35A,35B	SB-13 [2871]	25-Nwall**	7.5YR-6/6 reddish yellow
				SB-4 [2772]	15-30	7.5YR-6/4 light brown
				SB-5 [2773]	30-50	7.5YR-6/4 light brown
				SB-16 [2873]	35-Nwall**	7.5YR-5/6 strong brown
50-75	Bk2	B horizon, reacher in carbonate, about 25-50%, difussive, column structure	60A,60B	SB-6 [2774]	50-75	light yellowish brown
				SB-11 [2872]	60-Wwall**	10YR-6/4 light yellowish brown
75-115	Bbkm	hard carbonate horizon, 75% carbonate, darker sediment, column stucture		SB-7 [2775]	75-90	10YR-7/4 very pale brown
				SB-8 [2776]	90-115	10YR-7/3 pale brown

* Sensors names were numbered by depths in cm; installed at different walls of the trench - A: western wall, with bare soil surface; B: Eastern wall, profile lays under a bush.

** Sampled with in-situ soil sampler (100ml cups, 5cm diameter) ; collected from - Nwall = northern wall of the trench; Wwall = western wall of the trench



Appendix iii-1 Soil profile of Sde Boker monitoring station previous to sensors installation. Viewed here are the northern and eastern walls in the trench. Sensors that were marked by the letter B, were later installed into the undisturbed soil in the eastern wall, under the bush. (11.08.2017).



Appendix iii-2 Soil profile of Sde Boker monitoring station. Open trench, view direction: North. Sensors were installed into the undisturbed soil in the western wall (A), under bare soil, under the bush, and into the undisturbed soil in the eastern wall (B) under bare soil.

Appendix IV – Compartment model parametrization: soil samples, monitoring data and calibration procedure

1. [IV.I - Soil data](#)

Analysis of soil texture and water content data from two sites with soil water monitoring stations were crucial for the calibration and validation processes. These data also helped to establish confidence in the model results for other sites.

Nine and eleven soil samples were taken from the Gilat and Sde-Boker sites respectively, in vertical intervals of 10-20cm. Water content at the sampling time for each sample was estimated by weighing it before and after it was dried at 50°C for 72 h. 9 and three of the samples from Gilat and Sde-Boker sites, respectively, were sampled using an in situ soil sampler (100ml cups) for soil density measurement, assuming particle density of 2.65 g/cm³. These densities were used to transfer water contents from weight percentage units into volumetric percentage of water contents. Water contents of Gilat site samples were used as initial water content profile in the calibration procedure.

All samples were sieved for 2 mm and measured for particle size distribution using laser diffraction device (Malvern Mastersizer MS-2000), following the procedure of Crouvi et al., 2008. Values of θ_r and FC were calculated using the Rosetta software (Schaap and Van Genuchten, 2001) that uses pedotransfer-functions to estimate hydraulic properties of soils with texture and bulk density data. These data were taken into consideration when deciding the WHC parameters and were later compared with the calibration results. The estimations of soil water holding parameters in the Rosseta are based on empirical data with many records of much more humid, forested areas with higher clay contents and therefore the estimations of these parameters should be taken carefully and therefore the FC parameter was not prescribed but tested with the calibration procedure.

2. [IV.II - Sensors data](#)

In Gilat site, seven sensors were installed at five different depths: 10cm (R10,L10), 27cm (R27), 45cm (R45,L45), 60cm (L60) and 80cm (R80). Installation was made more or less in two columns (R-right, and L-left) in order to minimize water flow interferences.

In Sde Boker Site, 8 sensors were installed at four different depths with four repetitions: 10cm (10A, 10B), 25cm (25A, 25B), 35cm (35A, 35B) and 60cm (60A, 60B). One vertical

sensors alignment was inserted to the soil profile with bare soil surface (assigned with A), and the other was aligned under a bush (assigned with B).

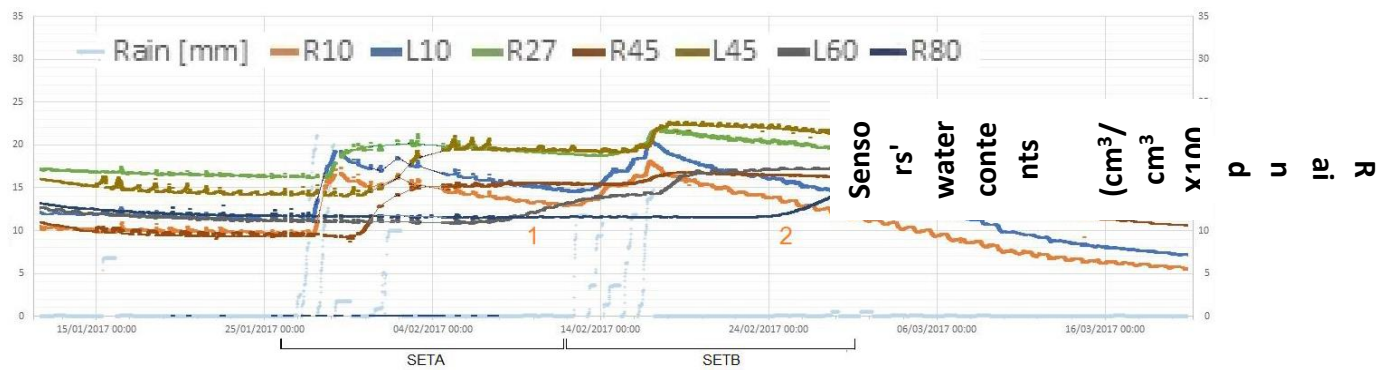
The stations log the data at 10 minutes intervals and update the water contents time series once a day. The installation of the sensors involved adding wet mud (taken from the same soil depth) around the sensors to make sure that there was as much contact as possible between the sensor and the surrounding soil. The water content around the sensors dropped rapidly in the following 10-20 days as the mud dried out, to a stable value in Gilat (Appendix iv-1). In Sde Boker stable values reached after 1-2 months.

Water content was recorded over two seasons in Gilat, and over one season in Sde Boker. The data-series were analyzed to find semi-stable high and low limits of water contents for each of the sensors, to establish expected values for the WHC limits.

Estimate of $\theta_r = 0.02 \text{ cm}^3/\text{cm}^3$ from Mualem (1976) for Gilat soil matched the lower limits of water content in R10 and L10 (10 cm depth). This value was taken as the lower limit of the WHC for all compartments; the upper limit was determined through the calibration procedure. According to soil data, FC is estimated to range between $0.19\text{-}0.21 \text{ cm}^3/\text{cm}^3$ both in the Gilat and Sde Boker soils. Sensors data support this range. Instead of prescribing it to be an average of these estimates, I decided to calibrate for it and therefore inserted a large range of $0.1\text{-}0.22 \text{ cm}^3/\text{cm}^3$.

3. [IV.III - Calibration-Validation](#)

The monitoring station in Gilat has registered two rainfall events of 4-6 consecutive rainy days each in the winter of 2016/17. SETA and SETB are two 16-17 days long time series that include one rain event at the beginning of each period, following with about 10 dry days (Appendix iv-1). At the end of each of the periods, the water distribution seem to arrive to its final depth – inferred according to an increase to a steady value of water content in the deep sensors: L60 at the end of SETA, and R80 at the end of SETB (numbered 1 and 2 respectively in Figure 9). The time series include the water contents of each of the stations' sensors at 22:00hr of each day, the daily rainfall and the daily PM-PET (penman-monteith type of PET) – weather data was received from the agro-meteorological station of the Gilat Research Institute (Ministry of Agriculture).



Appendix iv-1 Data series for calibration (SETB) and validation (SETA) of the compartment model – including daily rainfall and daily Penman-Monteith PET from Gilat meteorological station (Ministry of Agriculture), and soil water contents from monitoring sensors (10min intervals).. The timing when the deepest sensor reacted to the rainfall events in set A and set B, are indicated by numbers 1 and 2 respectively. The water content profile in timing 1 and 2 was compared with the modeled water contents for the same dates.

The first event occurred three weeks after the installation of the station at 5.1.2017 that included artificial water addition around the sensors, and about one week after this high water content around the sensors decreased to a stable value (~ 17.1.2017). Estimation for an initial water content profile for the model calibration was conducted in three steps:

1. First, the water content of the compartments was assigned according to the water content that was measured from the soil samples (section 5.1.4.1). Compartment depths between samples received an averaged value.
2. Then the added water contents were calculated for each sensor's depth as the difference between sensors' data and sampled water content.
3. After a period of distribution, the stable values of the sensors' water contents at 17.1.2017, were considered true values of the 4cm range surrounding each sensor. and the rest of the added water content calculated at step 2, was divided equally between the adjacent compartments to the sensor's depth, as an addition to the sampled profile.

This was necessary because the model doesn't include matrix flow of water.

Daily WD data in soils does not exist in records. The process of wetting and drying in the compartment model are instantaneous and therefore produce a product that can be only be tested against the end of the wetting process. The model was calibrated using - (1) a comparison between the modeled and the measured profiles of soil water contents at the end of each period (SETB for calibration and SETA for reinforcement) and, (2) by

denying inconsistencies between the WDs calculated by the model and the "breakthrough curves" indicated by the sensors.

Comparing water content profiles at the end of each period: The water content reported in each sensor compared with the water content predicted by the model for the same depth as the sensor. In depths where two sensors were installed (10cm, 45cm), the mean water content was taken. The sensors' data is representative of about ± 2 cm radius around the sensor, and therefore, the volumetric water content given by the sensors ($\text{cm}^3/\text{cm}^3 \times 100$), was translated into 1D water depth (mm) out of 4cm soil layers. The compartment size was prescribed to 4 cm (just for the calibration procedure).

The distribution of water contents was compared as follows: the 3rd compartment (8-12cm depth) represent sensors L10/R10, the 7th compartment (24-28cm depth) represent sensor R27; the 12th compartment (44-48cm depth) represent L45/R45; the 16th compartment (60- 64) represent sensor L60; and the water content in the 21th compartment (80-84cm depth) should represent the measurement in sensor R80.

Optimal set of parameters was chosen for minimal differences between the sensors measurements and the simulated values according to mean absolute difference (MAD) and the Root Mean Square Difference:

$$MAD(mm) = \frac{\sum_{10cm}^{80cm} |measured\ water\ content - simulated\ water\ content|}{number\ of\ compared\ values = 5}$$

$$RMSD(mm) = \frac{\sqrt{\sum_{10cm}^{80cm} (measured\ water\ content - simulated\ water\ content)^2}}{number\ of\ compared\ values = 5}$$

Inputs to the calibration procedure included:

1. Daily rainfall and daily PM-PET of period 5.1.17-28.2.17 (that include SETA +SETB)
2. Compartment size of 4cm, soil depth of 200cm (50 compartments)
3. Minimal water content at each compartment was set to $\theta_r = 0.02 \text{ cm}^3/\text{cm}^3$
4. Maximal water content at each compartment was calibrated for values of $FC = 0.1 - 0.22 \text{ cm}^3/\text{cm}^3$, verifying that with $FC = 0.19 \text{ cm}^3/\text{cm}^3$ the model produce optimal results.
5. The crop coefficient, K_c was calibrated in the range of $K_c = 0.2 - 3$.

Water contents were given in cm^3/cm^3 for convenience, it was translated into mm/4cm of water depths within the model.

The assumptions inherent in the calibration procedure were as follows:

- (1) The measurements of the daily rainfall in Gilat meteorological station are a good estimate of the depth of water that was added to the soil profile that day (i.e., all rainfall depth infiltrated the profile, no losses to runoff or interception).
- (2) The redistribution of water originated from several rain events was assumed to stop at the day where the lowermost sensor had reacted with increased water content to a semi-steady value. If this semi-steady value is lower than the maximal WHC of the layer, it means that the downward water flow would not proceed to deeper layers.
- (3) Evapotranspiration starts lowering the soil water-content from top to bottom with no gradient decrease with depth.
- (4) The water content distribution in the soil profile at the timing when the downward redistribution was achieved, is the combined result of both the downward distribution process and the evapotranspiration process. And therefore can be a somewhat reliable test to calibrate the WHC and the Kc parameters.
- (5) The soil column is homogeneous with respect to its water-holding properties (according to the results of soil textures and Rosetta estimates for FC and θ_r this seemed to be justified)

Appendix V – Test statistics of the synthetic rainfall data series

The following 4 tables compare between synthetic data series of rainfall produced by the rainfall generator with measured data series from 4 meteorological stations of the study site:

Sde Boker, Be'er Sheva, Gilat and Be'eri.

I tested results of 100 simulations for each site, with T,F and KS tests and the percentage of none rejected similarity to the measured data is presented in the tables.

Scores of more than 70% are emphasized with color.

Comparisons were made also between an earlier version of the rainfall generator that was based on empirical distribution of the measured meteorological data and the current version which is based on fitted gauss distributions. Both versions produced rainfalls with similar properties of the measured data.

site:	SdeBoker		52 years of dataX100					Parameters for synthetic series: A=2.7858 B=0.76 Fdry=0.76 Fwet=0.88						
data-series	measured		SynthEmp15			T	F	KS	SynthGauss			T	F	KS
Distributions	mean	std	mean	std	err	% not rejected			mean	std	err	% not rejected		
Annual rainfall (mm)	89.71	39.5	89.1	31.7	1%	100	53	97	91.72	32.26	-2%	99	69	91
Daily depths (mm)	3.37	5	3.4	4.3	0%	100	0	0	3.39	4.37	-1%	99	1	0
Annual mean daily depth (mm)	3.40	1	3.4	0.9	1%	100	0	75	3.39	0.87	0%	100	4	84
Number of wet days per year	26.64	7	26.5	6.6	1%	100	96	100	27.07	6.63	-2%	100	94	99
Number of rain events per year*	15.77	4	15.4	3.3	2%	100	55	100	15.89	3.31	-1%	100	62	100
Events depths (mm)	5.68	10	5.8	7.9	-2%	100	0	0	5.76	7.92	-1%	99	1	0
Annual mean events depths (mm)	5.87	3	5.8	1.8	1%	100	8	76	5.80	1.79	1%	100	8	71
Events durations (days)	1.69	1	1.7	1.1	-2%	98	22	100	1.70	1.17	-1%	97	14	95
Annual mean events durations (days)	1.71	0.3	1.7	0.3	-1%	99	99	100	1.71	0.30	0%	98	95	100
Frequency of extreem daily depths (p99BeerSheva)	0.27	1	0.1	0.3	59%	41	9	100	0.12	0.34	56%	52	11	100
Frequency of extreem daily depths (p99Gilat)	0.06	0	0.0	0.1	84%	48	1	100	0.01	0.07	84%	52	2	100
extreem daily depth (mm)****	25.79		20.8	1.3	19%				20.99	1.53	19%			
Dry Spells (days) 0.1mm event seperation criterion	11.97	10.7	12.1	10.0	-1%	100	47	0	13.51	12.49	-13%	6	9	0
Annual mean dry spells (days) - depth of event separation criterion: 0.1 mm	12.62	4	12.6	3.1	0%	100	73	99	13.97	3.48	-11%	40	92	38
Annual std of dry spells (days) - depth of event separation criterion: 0.1 mm	10.53	4	9.8	3.7	7%	93	82	98	11.97	4.84	-14%	60	76	73
Dry Spells (days) 2mm event seperation criterion	19.50	17	16.9	14.8	13%	14	15	66	18.15	16.80	7%	77	87	87
Annual mean dry spells (days) - depth of event separation criterion: 2 mm	21.44	8	18.5	7.0	14%	29	71	22	19.59	7.28	9%	70	74	80
Annual std of dry spells (days) - depth of event separation criterion: 2 mm	16.54	7	14.6	6.8	12%	67	81	73	16.18	7.51	2%	98	86	96

site	Beer Sheva		52 years of dataX100					
			Parameters for synthetic series: A=3.89 B=0.76 Fdry=1.05 Fwet=1.02					
data-series	measured		SynthGauss		err	T	F	KS
Distributions	mean	std	mean	std	%	% not rejected		
Annual rainfall (mm)	191.6	72.0	181.59	52.7 1	5%	97	38	97
Daily depths (mm)	4.8	7	4.65	6.01	4%	92	0	0
Annual mean daily depth (mm)	4.7	1	4.65	0.98	2%	99	80	10 0
Number of wet days per year	39.6	10	39.05	7.96	1%	10 0	79	99
Number of rain events per year	20.5	4	20.31	3.52	1%	10 0	86	10 0
Events depths (mm)	9.6	16	8.91	12.1 2	7%	91	0	0
Annual mean events depths (mm)	9.3	3	9.00	2.40	3%	10 0	44	10 0
Events durations (days)	1.9	1	1.92	1.47	0%	99	2	20
Annual mean events durations (days)	1.9	0.3	1.94	0.32	0%	99	98	99
Frequency of extreme daily depths (p99Gilat)	0.4	1	0.18	0.42	54 %	51	10	10 0
Frequency of extreme daily depths (p99BeerSheva)	0.2	1	0.08	0.28	63 %	62	9	10 0
Extreme daily depth $\geq$ 99 th percentile (mm)	34.6		28.55	1.73	17 %			
Dry Spells (days) 0.1mm event separation criterion	10.2	10.2	11.04	10.3 5	-8%	64	68	0
Annual mean dry spells (days) - depth of event separation criterion: 0.1 mm	10.5	2	11.28	2.33	-7%	73	97	80
Annual std of dry spells (days) - depth of event separation criterion: 0.1 mm	9.4	5	9.90	3.88	-5%	99	41	51
Dry Spells (days) 2mm event separation criterion	13.3	12	13.17	12.6 7	1%	10 0	57	81
Annual mean dry spells (days) - depth of event separation criterion: 2 mm	14.3	4	13.71	3.63	4%	98	70	99
Annual std of dry spells (days) - depth of event separation criterion: 2 mm	11.4	5	12.21	4.89	-7%	98	88	99

site	Gilat		42 years of dataX100						Parameters for synthetic series: A=5.45 B=0.76 Fdry=1 Fwet=1					
data-series	measured		SynthEmp15			T	F	KS	SynthGauss			T	F	KS
Distributions	mean	std	mean	std	err	% not rejected			mean	std	err	% not rejected		
Annual rainfall (mm)	237.6	81.2	236.4	70.9	1%	100	93	99	239.8	73.2	-1%	100	93	99
Daily depths (mm)	6.5	9	6.5	8.5	-1%	100	53	9	6.5	8.5	0%	100	55	3
Annual mean daily depth (mm)	6.5	2	6.5	1.4	-1%	100	100	100	6.5	1.4	0%	100	97	100
Number of wet days per year	36.6	9	36.3	7.7	1%	100	87	99	36.9	7.6	-1%	99	89	99
Number of rain events per year*	19.0	4	19.0	3.3	0%	100	60	100	19.6	3.5	-4%	98	73	98
Events depths (mm)	13.0	21	12.5	16.9	4%	99	0	0	12.2	16.8	6%	97	2	0
Annual mean events depths (mm)	12.8	4	12.5	3.4	3%	99	49	98	12.3	3.4	4%	100	57	100
Events durations (days)	1.9	1	1.9	1.4	1%	99	57	97	1.9	1.4	3%	95	39	59
Annual mean events durations (days)	1.9	0.4	1.9	0.3	2%	100	89	99	1.9	0.3	3%	98	86	98
Frequency of extreme daily depths (p99Gilat)	0.4	1	0.3	0.6	15%	99	82	100	0.3	0.6	15%	98	81	100
extreme daily depth (mm)****	42.7		40.8	3.3	4%				40.6	2.8	5%			
Dry Spells (days) 0.1mm event separation criterion	9.8	8.3	10.1	8.2	-2%	98	76	0	11.4	10.7	-16%	2	0	0
Annual mean dry spells (days) - depth of event separation criterion: 0.1 mm	10.3	3	10.3	2.0	-1%	99	40	97	11.7	2.5	-14%	23	85	5
Annual std of dry spells (days) - depth of event separation criterion: 0.1 mm	8.1	4	8.0	2.9	2%	100	70	100	10.2	4.0	-25%	24	86	25
Dry Spells (days) 2mm event separation criterion	13.1	12	11.7	10.0	11%	34	2	74	13.0	12.5	1%	100	75	88
Annual mean dry spells (days) - depth of event separation criterion: 2 mm	14.3	6	12.2	3.0	15%	47	1	71	13.4	3.4	6%	100	2	100
Annual std of dry spells (days) - depth of event separation criterion: 2 mm	12.1	7	9.8	3.6	19%	53	0	93	12.0	4.8	1%	100	23	98

site	Beerli		68 years of dataX100			Parameters for synthetic series: A=7.8588 B=0.7603 ed=1.02 ew=1.05								
data-series	measured		SynthEmp15 err			T	F	KS	SynthGauss err			T	F	KS
Distributions	mean	std	mean	std	%				mean	std	%			
Annual rainfall (mm)	352.0	138.9	357.3	107.6	1%	100	42	84	365.3	106.3	4%	100	37	71
Daily depths (mm)	8.9	12	9	12.4	5%	82	26	18	9.4	12.3	5%	83	33	22
Annual mean daily depth (mm)	8.8	3	9	2.0	6%	86	47	77	9.4	2.0	6%	86	40	73
Number of wet days per year	39.4	9	38	8.1	-3%	94	95	100	39.1	8.0	-1%	100	92	100
Number of rain events per year*	19.8	3	19	3.3	-3%	92	100	100	19.8	3.4	0%	100	100	100
Events depths (mm)	18.7	29	19	25.3	0%	100	3	0	18.4	25.3	-1%	100	8	0
Annual mean events depths (mm)	18.0	7	19	5.2	5%	100	18	71	18.6	5.0	3%	99	8	82
Events durations (days)	2.0	1	2	1.5	0%	100	18	76	2.0	1.5	-1%	99	6	15
Annual mean events durations (days)	2.0	0.3	2.0	0.4	1%	99	97	99	2.0	0.3	0%	99	98	98
Frequency of extreem daily depths (p99Beerli)	0.4	1	0	0.7	17%	98	82	97	0.5	0.7	18%	98	79	99
Frequency of extreem daily depths (p99Gilat)	1.0	1	1	1.1	13%	95	94	98	1.1	1.1	15%	96	93	99
extreem daily depth (mm)****	55.3		58.8	3.3	6%				58.4	3.3	6%			
Dry Spells (days) 0.1mm event separation criterion	9.8	8.2	10.0	8.2	2%	99	76	0	11.2	10.5	14%	0	0	0
Annual mean dry spells (days) - depth of event separation criterion: 0.1 mm	10.1	2	10	2.1	2%	99	88	99	11.5	2.4	14%	1	95	1
Annual std of dry spells (days) - depth of event separation criterion: 0.1 mm	7.9	3	8	2.9	0%	99	79	97	10.1	3.9	28%	1	58	1
Dry Spells (days) 2mm event separation criterion	11.8	10	11	9.3	-8%	35	58	35	12.1	11.7	2%	99	0	81
Annual mean dry spells (days) - depth of event separation criterion: 2 mm	12.1	3	11	2.6	-7%	46	91	64	12.4	3.0	2%	98	82	100
Annual std of dry spells (days) - depth of event separation criterion: 2 mm	9.5	4	9	3.2	-5%	94	82	98	11.2	4.4	18%	28	63	52

Appendix VI – Effects of weather parameters on depths of Bk proxies and on mean weather properties.

In the following tables are results of local sensitivity for 20% changes to weather parameters in the northern Negev (Figure 20). Mean shallowing and deepening effects for simulations of four sites of Be'eri, Gilat, Be'er-Sheva and Sde-Boker are presented, showing:

1. Asymmetry of the sensitivity of the proxies to changes promoting deepening and shallowing effects.
2. The control of Fw and EventsDepths on deepening of the proxies
3. Differences in the sensitivities of MeanWD and Index30 to the B parameter.

Mean Shallowing effects:							
	Index30	annual rain	MeanWD	EventsN	EventsDurations	EventsDepth	DailyDepth
FPET+20%	-18%	-2%	-16%	0%	0%	0%	0%
Fd-20%	-13%	-16%	-14%	-16%	0%	-1%	0%
Fw-20%	-21%	-13%	-23%	4%	-16%	-17%	0%
A-20%	-27%	-20%	-29%	1%	0%	-21%	-20%
B-20%	-37%	-11%	-24%	1%	0%	-12%	-11%

Mean deepening effects							
	index30	annual rain	MeanWD	Events N	Events dur	Events depth	dailyDepth
FPET-20%	16%	-2%	15%	0%	0%	0%	0%
Fd+20%	13%	16%	15%	17%	0%	-1%	0%
Fw+20%	36%	18%	42%	-4%	24%	23%	0%
A+20%	31%	20%	38%	1%	0%	18%	20%
B+20%	34%	26%	15%	1%	0%	23%	25%

In the next page, the effects are presented for each site separately. Parameters and weather properties with the largest effects on Mean WD are painted with light grey colour – usually indicating Fw, EventsDuration and EventsDepths as the most controlling factors over the depth of the proxies, ranks 2 and 3 (coloured with darker grey) are usually given to the A and B parameters, also correlating with great effects to the EventsDepths. However the sensitivity of proxies' depths to these parameters varies from station to station.

Beerli

Weather par.	index30	annual rain	MeanWD	EventsN	Events dur	Events depth	dailyDepth
FPET+20%	-0.27	-0.06	-30%	0%	0%	0%	0%
FPET-20%	0.06	-0.06	2%	0%	0%	0%	0%
FPET+20%	-0.21	0.00	-20%				
FPET-20%	0.23	0.00	24%				
Fd-20%	-0.18	-16%	-23%	-17%	1%	0%	0%
Fd+20%	0.20	15%	23%	15%	1%	0%	0%
Fw-20%	-0.28	-14%	-36%	3%	-17%	-18%	0%
Fw+20%	0.48	20%	55%	-7%	30%	29%	0%
A-20%	-0.32	-20%	-43%	-1%	1%	-20%	-20%
A+20%	0.38	20%	43%	-1%	1%	20%	20%
B-20%	0.38	26%	14%	-1%	1%	25%	25%
B+20%	-0.40	-11%	-37%	-1%	1%	-11%	-11%

Gilat

Weather par.	index30	annual rain	MeanWD	EventsN	Events dur	Events depth	dailyDepth
FPET+20%	-0.14	0.03	-15%	0%	0%	0%	0%
FPET-20%	0.23	0.03	20%	0%	0%	0%	0%
FPET+20%	-0.20	0.00	-20%				
FPET-20%	0.23	0.00	23%				
Fd-20%	-0.13	-15%	-17%	-14%	-2%	-3%	0%
Fd+20%	0.12	16%	19%	20%	-3%	-4%	0%
Fw-20%	-0.22	-13%	-27%	7%	-18%	-20%	-1%
Fw+20%	0.37	19%	56%	-1%	21%	19%	0%
A-20%	-0.27	-19%	-34%	3%	-3%	-23%	-20%
A+20%	0.32	22%	55%	4%	-3%	15%	20%
B-20%	0.33	26%	28%	4%	-3%	20%	25%
B+20%	-0.37	-10%	-30%	3%	-2%	-15%	-11%

Be'er-Sheva

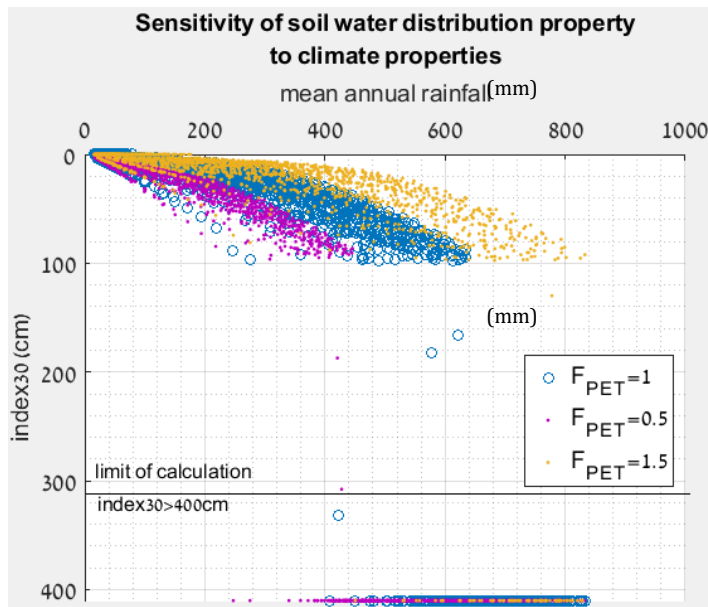
Weather par.	index30	annual rain	MeanWD	EventsN	Events dur	Events depth	dailyDepth
FPET+20%	-0.20	-0.07	-0.14	0%	0%	0%	0%
FPET-20%	0.14	-0.07	0.10	0%	0%	0%	0%
FPET+20%	-0.17	0.00	-0.12				
FPET-20%	0.25	0.00	0.18				
Fd-20%	-0.10	-16%	-0.10	-16%	1%	2%	0%
Fd+20%	0.11	16%	0.13	15%	1%	1%	0%
Fw-20%	-0.21	-13%	-0.18	4%	-16%	-16%	-1%
Fw+20%	0.37	19%	0.43	-5%	27%	28%	0%
A-20%	-0.24	-20%	-0.22	0%	1%	-19%	-20%
A+20%	0.29	20%	0.37	0%	1%	21%	20%
B-20%	0.31	25%	0.19	0%	1%	26%	25%
B+20%	-0.36	-11%	-0.17	0%	1%	-10%	-11%

SB

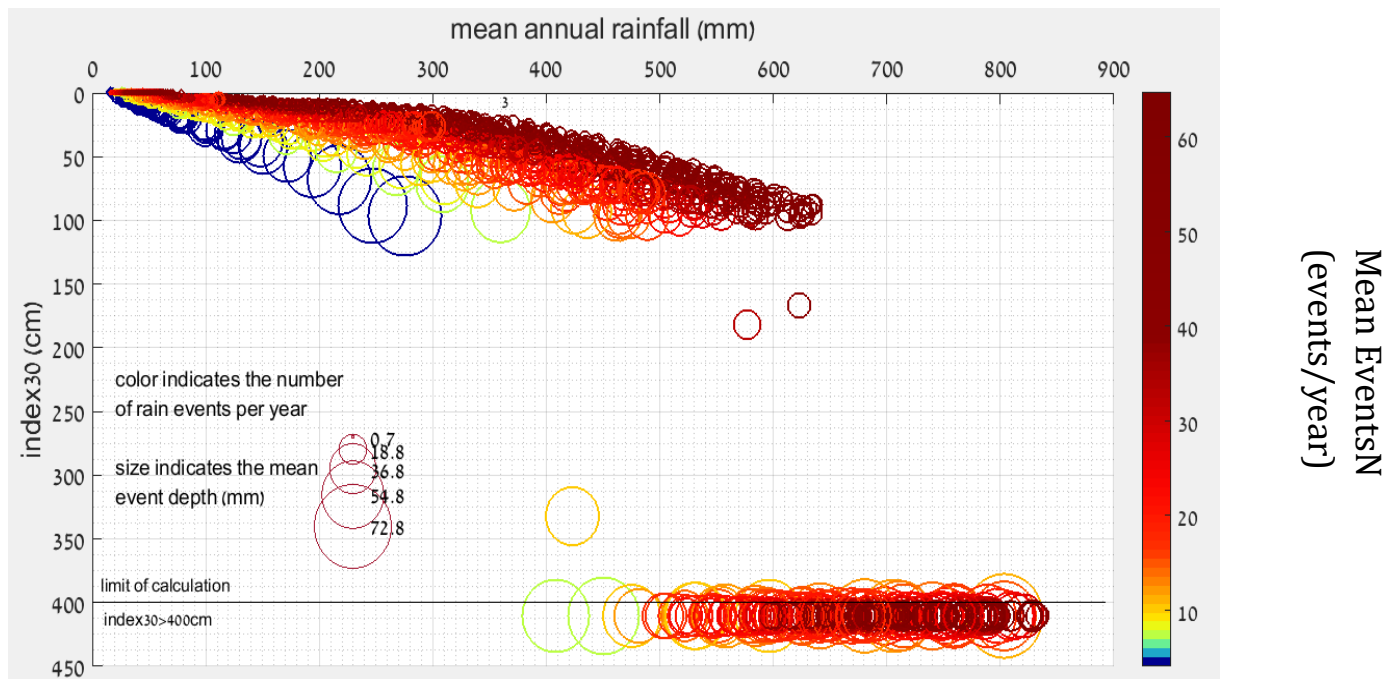
Weather par.	index30	annual rain	MeanWD	EventsN	Events dur	Events depth	dailyDepth
FPET+20%	-0.12	0.05	-0.06	0%	0%	0%	0%
FPET-20%	0.20	0.05	0.27	0%	0%	0%	0%
FPET+20%	-0.14	0.00	-0.08				
FPET-20%	0.21	0.00	0.11				
Fd-20%	-11%	-0.18	-0.06	-17%	0%	-2%	0%
Fd+20%	9%	0.17	0.06	18%	0%	-2%	0%
Fw-20%	-15%	-0.11	-0.10	3%	-13%	-15%	0%
Fw+20%	24%	0.14	0.15	-2%	18%	16%	0%
A-20%	-24%	-0.20	-0.16	1%	0%	-21%	-20%
A+20%	26%	0.18	0.16	1%	0%	16%	19%
B-20%	38%	0.25	0.02	1%	0%	22%	25%
B+20%	-33%	-0.12	-0.12	1%	0%	-13%	-11%

Appendix VII – Results of global sensitivity for Index30 proxy

Here are some example of the results for Index30 proxy for depth to Bk. In general, the global sensitivity results trend with mean annual rainfall and affected by the other weather properties in similar ways to MeanWD. Figures here may be compared with Figure 24 ,Figure 25.



Appendix vii-1 Global sensitivity analysis for the effect of rainfall and evaporation parameters on Index30 as the depths to carbonate proxy. About 1500 variations of rainfall properties were simulated for three different F_{PET} . Results are concentrated either in depths of 0-100cm or at depths>400cm which are deeper than the simulated profile.



Appendix vii-2 Effect of means of: events per year, events depths and annual rainfall on trends and depths of Index30 carbonate horizon proxy

מידת ההשפעה של תכונות אקלים על התפלגות המים ארוכת הטווח בקרקות צחיחות וחצי-צחיחות עם השלכות על היווצרות מלחים בקרקע

גשמים הם הגורם העיקרי לתנועת מלחים בקרקעות. באזורים צחיחים ולצחיחים למחצה, צבירה של קרבונט וגבס מתרחשת באופקי קרקע בעומקים רדודים בעקבות אידוי גבוה ומעט גשמים. מקובל להשתמש בתצפיות של אופקי קרבונט לשחזור ממוצע הגשמים בתקופות עתיקות כיוון שידוע שעומקם גדל עם הגשם השנתי הממוצע. למרות שתכונות נוספות של האקלים, כמו התפלגות הגשמים במהלך השנה, משפיעות אף הן על עומקי הצבירה של המלחים, מעט עבודות בחנו השפעה זו. במחקר זה פיתחתי מודל חידור מים לקרקע יחד עם מודל סטוכסטי של מזג אוויר לצורך הדמייה ארוכת שנים של התפלגות עומקי ההרטבה בקרקעות הנגב הצפוני בישראל. מהרצות המודל, אותרו תכונות של התפלגות מים בקרקע המתאימות לשמש כסמנים לעומקי צבירה של קרבונט וביניהן: עומק ההרטבה הממוצע, והעומק בו שטף המים השנתי הינו 30% מערך הגשם השנתי. בעזרת סמנים אלה ניתן לכמת את מידת ההשפעה של תכונות מזג אוויר שונות על עומקי הצבירה של הקרבונט. על פי ההדמיות שביצעתי, בדומה לעומקים של אופקי הקרבונט, הסמנים מעמיקים עם הגדלת הגשם השנתי הממוצע, אך תכונות אקלימיות אחרות משפיעות על התפלגות העומקים בטווח של עד 75 ס"מ. כאשר מקבעים את הגשם השנתי הממוצע, עומק הסמן נקבע בעיקר ע"י עובי אירועי הגשם. והתוצאות מתקבלות בתחום של עד 25 ס"מ כתלות בממוצעים של עובי אירועי גשם או של מספר האירועים השנתי. מידת ההשפעה של שינויים בתכונות האקלימיות על עומק הסמנים גדלה עם עליה בגשם השנתי וירידה באידוי. ממבחי רגישות מקומית של הסמנים ניתן להסיק שבאזורים עם גשם שנתי נמוך מ-200 מ"מ לשנה, שינוי של כ-20% בתכונות ממוצעות של האקלים יגרום לשינוי קטן מאוד בעומק הסמנים הקטן משגיאת המדידה, ולא ניתן יהיה לזהותו בשדה באמצעות תצפיות של עומקים לאופקי קרבונט. השפעת האידוי על עומקי האופקים ועל מגמתם עם הגשם השנתי מתבטאת בהבדלים הגדולים הקיימים בין עומקים לאופקי קרבונט באזורים עם גשם שנתי זהה אך עונתיות שונה. ניתן לייצר תרחישי מזג אוויר שונים על מנת לענות על שאלות לגבי שינויי אקלים בעבר והשפעותיהם של שינויים עתידיים. על מנת לכמת את מידות ההשפעה של תקופות יובש שבין אירועי גשם ושל אירועי קיצון יש לערוך הרצות המוגדרות באופן מכוון לשאלת המחקר. באזורים עם קרקעות בהרכב חולי יותר, מידות ההשפעה המתוארות לעיל צפויות להיות גבוהות יותר. תכונות נוספות של התפלגות ההרטבה בקרקעות נמצאו מתאימות לחיזוי עומקים לאופקי גבס ואלה רגישים יותר לשינויים במשטרי האקלים. לסיכום, הצגתי גישה לחקר של משטר הרטבת קרקעות בפרקי זמן ארוכים, וליחס שבין התפלגויות ההרטבה, תכונות אקלימיות ואופקי צבירה של קרבונט וגבס. מתוצאות המחקר ניתן לשפר פרשנויות של אקלים עבר המתבססות על תכונות של אופקי גבס וקרבונט קבורים. בגישה זו ניתן להשתמש גם על מנת להסיק מסקנות לגבי ההשפעות הפוטנציאליות של שינויי אקלים על זמינות מים לצמחיה ותנועות מזהמים ודשנים בקרקע.



המכון הגיאולוגי
משרד האנרגיה

מידת ההשפעה ארוכת הטווח של תכונות אקלים על התפלגות המים בקרקעות, והאם ניתן לקשר התפלגות זו לאופקי מלחים בקרקעות הלס של צפון הנגב

טלי הורוביץ

עבודה זו הוגשה כחיבור לקבלת תואר "מוסמך" באוניברסיטה העברית, ירושלים.

העבודה נעשתה בהדרכתם של:

ד"ר און כרובי, המכון הגיאולוגי, ירושלים.

פרופ' אפרת מורין, האוניברסיטה העברית, ירושלים.

