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MSC IN HYDROHASARDS

A generic framework for the identification of hydrological droughts through the propagation of runoff generation mechanisms in semi-arid catchments

MSc Thesis by

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ABSTRACT

The study investigates the identification of hydrological droughts for different runoff components in semi-arid catchments with the use of rainfall-runoff models. Daily observed rainfall, runoff and temperature data from Yermasoyia catchment in southern Cyprus are used in the TUWmodel in order to obtain the different response runoff components as well as soil moisture time series. The model is applied as a lumped and semi-lumped model conceptualizing the watershed into specific elevation zones. The hydrological deficits are derived according to the threshold level method. A monthly varying threshold and the inter-event and volume criterion pooling procedure was used in this study and was applied in all the aforementioned variables. The information that was acquired by the threshold level method and concern the duration and the start date of the event were used in order to create new time series that contain the information as a binary signal {0, 1}; where, an event of specific duration is represented by the same number of consecutive “1”. The new deficit time series are subjected into two different qualitative analyses in order investigate the lag time of drought event occurrences between the different components and identify the drought generating mechanism, i.e. a cross-correlation analysis and an event to event analysis.

Moreover, the drought events that were extracted from the lumped model are used to extract the general drought characteristics (e.g. mean duration, mean volume deficit) and they are being classified based on the typology. In the last part of the study a probabilistic analysis is performed in the annual maximum volume deficits, which investigates the fitting of the proper distribution in order to model the volume deficits.

ΠΕΡΙΛΗΨΗ

Η παρούσα μελέτη στοχεύει στη διερεύνηση υδρολογικών ξηρασιών στις διάφορες συνιστώσες της απορροής σε λεκάνες που χαρακτηρίζονται από ξηρό κλίμα, με την χρήση μοντέλων βροχής-απορροής. Ημερήσιες παρατηρήσεις βροχόπτωσης, απορροής και θερμοκρασίας από την λεκάνη της Γερμασόγιας στη νοτιά Κύπρο χρησιμοποιήθηκαν στο μοντέλο (TUWmodel), ώστε να εκτιμηθούν οι συνιστώσες τις ροής και οι τιμές εδαφικής υγρασίας. Η προσομοίωση του αδρομερούς μοντέλου έγινε σε για όλη τη λεκάνη καθώς και για σενάρια που περιέχουν την λεκάνη χωρισμένη σε συγκεκριμένες υψομετρικές ζώνες. Οι σειρές των υδρολογικών ελλειμμάτων υπολογίζονται βάσει του ορίου που θεωρούμε ότι η ροη βρίσκεται στα φυσιολογικά πλαίσια για την λεκάνη (threshold level method). Στη συγκεκριμένη περίπτωση εφαρμόστηκε ένα μηνιαία μεταβαλλόμενο όριο και τεχνικές που στοχεύουν στη σύμπτυξη των γεγονότων ξηρασίας (pooling methods) και απομονώνουν τις ξηρασίες μικρής διάρκειας. Οι πληροφορίες από την ανάλυση που αφορούν το αρχικό σημείο καθώς και τη διάρκεια των γεγονότων ξηρασίας, χρησιμοποιήθηκε για να δημιουργηθούν χρονοσειρές που περιχούν την πληροφορία με τη μορφή δυαδικού σήματος {0,1}, όπου ένα γεγονός συγκεκριμένης διάρκειας αναπαρίσταται από τον ίδιο αριθμό μονάδων στη χρονοσειρά (΄1΄). Οι νέες χρονοσειρές υπόκεινται δυο ειδών αναλύσεις για να διαπιστωθεί η χρονική καθυστέρηση εμφάνισης των γεγονότων ξηρασίας μεταξύ των συνιστωσών και να διερευνηθούν οι βασικοί γενεσιουργοί μηχανισμοί των ξηρασιών. Αυτές είναι: μια ανάλυση συσχέτισης (cross-correlation) που περιλαμβάνει όλο το μήκος τη σειράς και μια ανάλυση που εξετάζει τα γεγονότα κατ’ αντιστοιχία.

Τα γεγονότα υδρολογικής ξηρασίας, όπως εκτιμηθήκαν από το αδρομερές μοντέλο που αφόρα το σύνολο τη λεκάνης, χρησιμοποιήθηκαν ώστε να υπολογιστούν τα βασικά τους χαρακτηριστικά (μέση διάρκεια, μέσος όγκος ελλείμματος) και κατηγοριοποιούνται βάσει των ορισμών που υπάρχουν στη βιβλιογραφία. Επιπλέον στη μελέτη εφαρμόζεται μια πιθανοτική ανάλυση, συγκεκριμένα στις τιμές που αφορούν τα μέγιστα ετήσια ελλείμματα, που διερευνά την προσαρμογή θεωρητικών κατανομών στο δείγμα.

RÉSUMÉ

L’objectif de cette étude porte sur l’identification des sécheresses hydrologiques selon différents composants du ruissellement dans des bassins versants semi-arides à l’aide de modèles Pluie-Débit. Des données journalières de pluie, débit et de température provenant de Yermasoyia un bassin versant se situant dans le sud de Chypre sont utilisées comme données d’entrées pour le TUWmodel. L’utilisation de ce modèle a pour but d’obtenir la réponse des différents constituants composant le ruissellement comme l’humidité du sol en fonction du temps. Le model est utilisé comme un modèle « lumped » et « semi-lumped » où le bassin est catégorisé selon l’altitude. Les déficits hydrologiques sont dérivés selon un niveau-seuil. Un niveau-seuil variant selon le mois et un critère de volume ont été utilisé dans cette étude et appliqué dans les variables mentionnées ci-dessus. La méthode du niveau-seuil permet de définir la durée et la date du début de l’évènement et ainsi de créer de nouvelles séries temporelles selon un système binaire {0, 1}; L’apparition d’un évènement et sa durée est caractérisé par la succession du nombre 1. Les nouvelles séries temporelles de déficits font l’objet de deux différentes analyses qualitatives dans le but d’examiner le temps de latence d’occurrence des sécheresses entre les différents constituants. Ces deux analyses qualitatives permettent aussi d’identifier les mécanismes générant une sécheresse, i.e. analyse de corrélation croisée et analyse d’évènements.

De plus les périodes de sécheresses modélisées par le modèle « lumped » servent à obtenir les caractéristiques générales liées à une sécheresse (ex. durée moyenne, déficit moyen de volume) et de les classées selon la typologie. Dans la dernière partie de l’étude une analyse probabiliste des maximums annuels pour les déficits de volume est produite. Cette analyse permet d’examiner la distribution suivie par les maximums annuels dans le but de modéliser les déficits de volume.

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INTRODUCTION

1.1 Droughts

Hydrological extreme events, such as floods and droughts affect societies around the world. These types of natural hazards are often spread around large regions and can affect economically and socially a significant amount of people. An interesting fact is that hydrological extreme events may occur in a yearly or seasonal basis in some parts of the world and can affect the quality of life as much as life itself for extended periods of time, sometimes for whole years. Even though flood events have much more visible impacts, droughts are considered as one of the most damaging hazards in terms of economic cost [Wilhite, 2000]. It is pointed out by studies [Tallaksen and Van Lanen, 2004; Sheffield and Wood, 2011] that droughts not only cover extensive areas (spatial scale) but have an important temporal scale lasting from months to years that can cause many problems e.g. water scarcity and water quality issues, crop irrigation failure, forest fires and electric production through hydroelectric plants reduction. Often there is confusion between a heat wave and a drought. Chang and Wallace [1987] have emphasized the distinction between heat wave and drought, noting that a typical time scale associated with a heat wave is on the order of a week, while a drought may persist for months or even years. Also, it is documented that in the period between 1900 and 2010, about 2 billion people were affected and more than 10 million people have died from the impacts of drought events, worldwide [EM-DAT, 2012; EEA, 2012]. Droughts are also referred to as 'the creeping disaster" [Wilhite, 2000; Mishra and Singh, 2010].

There are many severe drought events in recent years that indicate the recurring pattern of droughts and prove that there are imminent threats on global scale [Van Loon, 2013]. In 2012, two simultaneous drought events in central and southern USA and Russia induced an increase in food prices. In spring 2011, Western Europe faced severe water shortage and low water levels. In 2011, a long-lasting drought event caused mass migration, and life losses in Africa [Viste et al., 2012]. In 2010 and 2011, Russia experienced a drought and heat wave [Grumm, 2011], resulting in widespread forest fires [Huijnen et al., 2012]. In 2010, large parts of China were affected by drought, reducing food production [Lu et al., 2011], and in that same year Scandinavia faced drinking water shortage and hydropower production problems [Cattiaux et al., 2010]. In 2005 and 2010, the Amazon rain forest was affected by a severe lack of precipitation caused the reduction of vegetation mass and increased the release of CO2 into the atmosphere [Lewis et al., 2011]. Also, Australia was affected between 2002 and 2010 by severe multi-year drought event [McGrath et al., 2012].

Currently there is an increasing awareness and scientific interest in drought events. Attempts are also made in order to understand if the phenomenon has been deteriorating over the last decades and identify if there are significant trends on a global and on a continental scale [e.g. Hisdal et al., 2001; Seneviratne et al., 2012]. There is not yet a definite answer for a global scale upward trend, but as Seneviratne et al. [2012] indicate there is medium confidence that since 1950 some regions of the world such as, Southern Europe and West Africa experience more intense and longer droughts. Concerning Europe, Stahl et al. [2010] and Stahl et al. [2012b] also indicate lower streamflow values occurrences in southern and eastern European regions and generally increased streamflow values in western and northern regions. There are also scenarios that the impacts of the climate change which are suggesting a dryer and warmer Mediterranean region [IPCC, 2007] will lead to higher risks of heat waves and droughts [Seneviratne et al., 2012]. As a result, the number of organisations that exist in order to inform and educate the public has increased, for example, the Global Drought Monitor and the European Drought Centre. Also the Water Framework Directive of the European Constitution is encouraging the implementation of drought management plans as a preventive measure.

1.2 Drought definition and classification

It is intriguing enough that even though the general concept of drought is known to mankind from ancient years, as a general deficiency of water resources, there is no universal definition of the phenomenon. A very simple definition is that drought is a deficit of water compared to normal conditions [Sheffield and Wood, 2011]. It is plausible that the normal conditions, the sufficient duration and severity of an event to be characterized as a drought, the part of the hydrological cycle that the event occurs (e.g. rain, soil moisture, runoff), as well as, if there are any external influences that should be taken into consideration, may differ from case to case. Hence, the definition of drought is dependent on the objective of a study, which is very important when quantifying drought [Van Loon, 2013].

Some commonly used definitions define droughts based on the lack of rainfall [WMO, 1986; UN Secretariat General, 1994; Schneider, 1996; Linseley et al., 1959], the impacts that a deficit will have in the agriculture [FAO, 1983] or based on general and statistical characteristics of the area [Gumbel, 1963; Palmer, 1965]. Yevjevich

[1967] stated that widely diverse views of drought definitions are one of the principal obstacles to investigations of droughts.

Droughts are basically distinguished based on the variable that is used to describe the drought event and are separated into four categories [Mishra and Singh, 2010; Wilhite and Glantz, 1985; American Meteorological Society, 2004]. Meteorological droughts are caused by a precipitation deficiency, commonly combined with increased potential evapotranspiration. Soil moisture drought is a deficit of soil moisture, reducing the supply of moisture to vegetation. Soil moisture drought is also called agricultural drought, because it is strongly linked to crop failure. Hydrological drought is a broad term related to deficits concerning the surface and subsurface water. Socio-economic drought is associated with the impacts of the three above-mentioned types. It can refer to a failure of water resources systems to meet water demands and to ecological or health-related impacts of drought.

1.3 Propagation of droughts

The concept of drought propagation is based on the actual way the water is moving through the different components of the hydrological cycle. It is a rather complicated mechanism as it is a combination of several variables such as precipitation (input variable), evapotranspiration (related to temperature and vegetation of the region), soil moisture storage (depends on the antecedent conditions and lower groundwater drainage), surface and subsurface runoff (soil moisture depended) and the lower groundwater. Each component has a feedback on the layers that are below. For example, if a meteorological drought occurs, this deficit would have a direct effect on the components of runoff as well as in the soil moisture content. The hydraulic deficit will have a positive feedback with a different time frame on the soil moisture content and in ground water recharge.

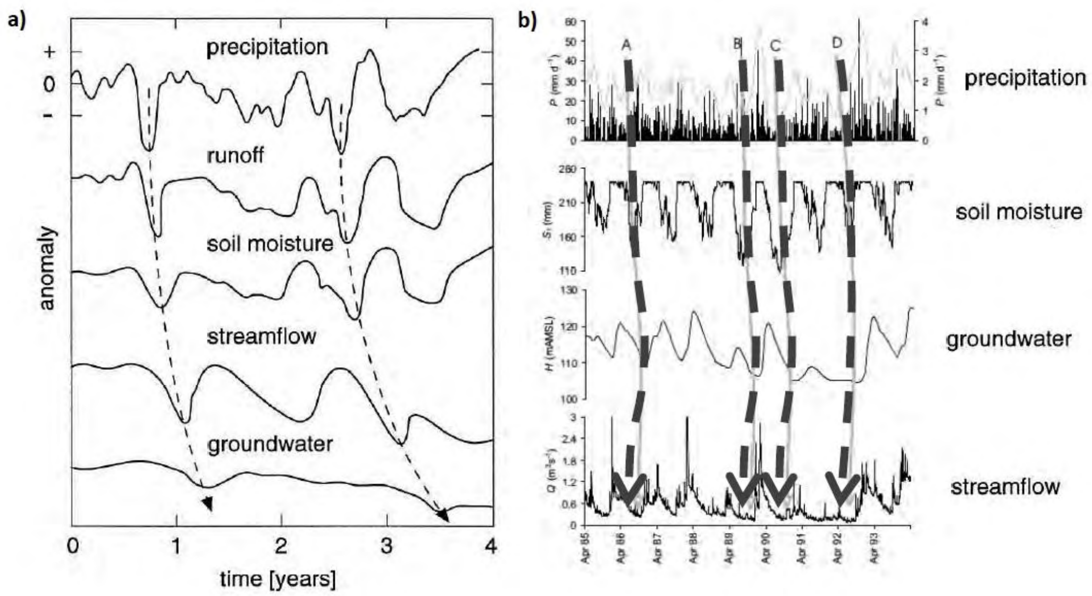

Figure 1.1: Propagation of a precipitation anomaly through the parts of the hydrological cycle for various variables (adapted from Van Loon, 2013), a) synthetic time series: 0 = mean, + = positive anomaly, – = negative anomaly [Changnon Jr, 1987], b) time series of the Pang catchment (UK): P = precipitation, Sr = soil moisture storage in the root zone, H = groundwater level, and Q = streamflow [Peters, 2003]. Propagation of drought events is indicated by the arrows.

Figure 1.1 is a schematic representation of the propagation of drought for various variables for a) a synthetic time series of anomalies Changnon Jr. [1987], and b) a non-modified time series example from the Pang catchment (UK) by Peters [2003]. The deficit transferring mechanism is outlined as the recession is being transferred through the different variables presenting a noticeable delay. Also the minor anomalies in the rainfall time series are attenuated and decreasing by each layer.

Figure 1.2 indicates basic definitions concerning the propagation of the drought event. All the minor events on the rain time series are pooled into one major event. There is a certain time delay between the start time of the events in the different components (from meteorological to soil moisture droughts) called lag from this point onwards. The lengthening is the end to end difference of the events. The events are attenuated through storage capacity and the severity of the event is decreased, suggesting that the ground slowly filters the drought propagation. It should be noted that the criteria concerning the characterisation of an event as a drought will be thoroughly explained in Chapter 3.

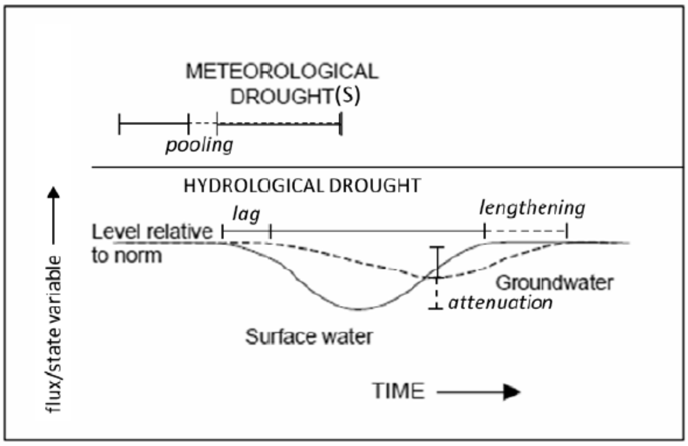

Figure 1.2: Main characteristics of the propagation of meteorological drought to hydrological drought: pooling, lag, attenuation, and lengthening (adapted from Van Loon, 2013)

1.4 Objectives of the study

The objective of this study is to investigate the propagation of droughts from meteorological anomalies (i.e. cause), to different components of the hydrological cycle (i.e. soil moisture and hydrological droughts) with the use of rainfall-runoff models. Specifically, the lag time between the occurrences in the different components is examined and analyzed through cross-correlation and event to event analysis. Moreover, the drought events are being characterized (Chapter 3) based on their connection to meteorological droughts and quantified based on the deficit volume. Additionally, the probabilistic analysis that is performed to the deficit volume annual maxima time series aims to indicate the use of the proper distributions in order to statistically forecast the severity of the droughts in the different components.

The study is targeting to drought management applications. It stands as a methodology framework in order to identify and estimate the occurrence of droughts in semi-arid catchments in different components of the hydrologic cycle. The procedures that will be later explained, contain a qualitative (i.e. time lag identification), a quantitative analysis that concern the volume deficit and a probabilistic analysis. The probabilistic analysis provides an overall characterization of the basin concerning the drought events and is orientated to long term drought management and infrastructure design (such as reservoirs).

1.5 Outline of the study

The study is organized as follows: Chapter 2 describes the study area and the data set that was used in the study. Also it contains a preliminary analysis indicating some particularities in the data set; Chapter 3 explains the methodology framework, the theory and the tools that were used in this study. Specifically it contains information about the rainfall-runoff model and the simulations that were performed, about the threshold level and pooling method, the lag identification procedure and the probabilistic analysis; Chapter 4 illustrates the results of the aforementioned; in Chapter 5 the results are being analyzed and discusses and Chapter 6 holds the conclusion.

2 STUDY WATERSHED AND DATABASE

This section regards the selected area and the dataset used in the study. Apart from the basic morphological and climatological characteristics of the catchment, it describes the dataset that was analysed and contains a preliminary analysis highlighting troubling issues that will be discussed and resolved further in the study.

2.1 Study watershed

The selected catchment for the study is Yermasoyia in southern Cyprus. The basin has a total area of 157 km^2 and the elevation varies from 70m up to 1540m almost at the top of Mount Troodos with a mean elevation 572m. At the outlet point of the basin there is a dam with storage yield up to 14 million m^3. The dam was constructed in 1968 in order to improve the field irrigation and the municipality's water demands. Figure 2.1 illustrates the catchment as well as the river network and the gauge stations' elevations. It should be noted that the certain cathcment has also been studied by Fotakis et al. [2014]. Nontheless geologic and vegetation coverage characteristics of the basin are included that were not examined in the present study.

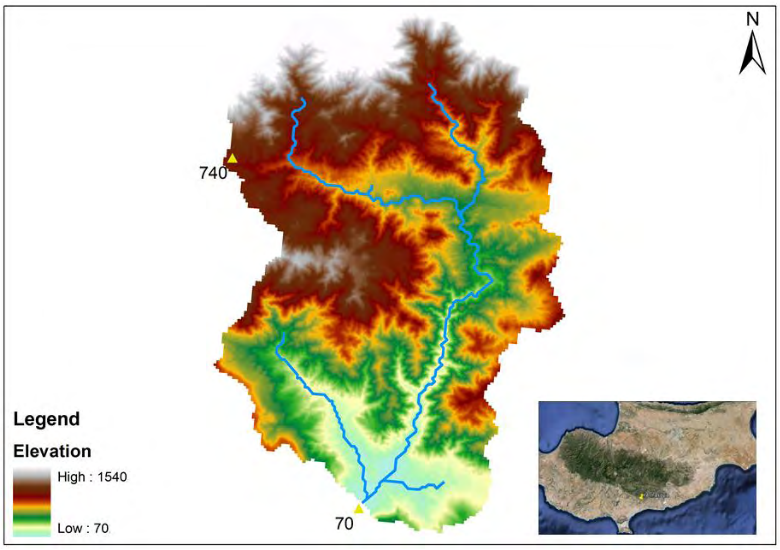

Figure 2.1: Yermasoyia catchment. The position and the elevation of gauging stations is noted.

Cyprus has a subtropical climate - Mediterranean and Semi-arid type (in the north-eastern part of island) - according to Köppen climate classification signs Csa and BSh [Peel et al., 2007], with very mild winters (on the coast) and warm to hot summers. Snow is possible only in the Troodos Mountain in the central part of island. Rain occurs mainly in winter, with summer being generally dry. Figure 2.2 presents the monthly average temperature and precipitation height in Limassol, the municipality that Yermasoyia belongs and Troodos Mountain.

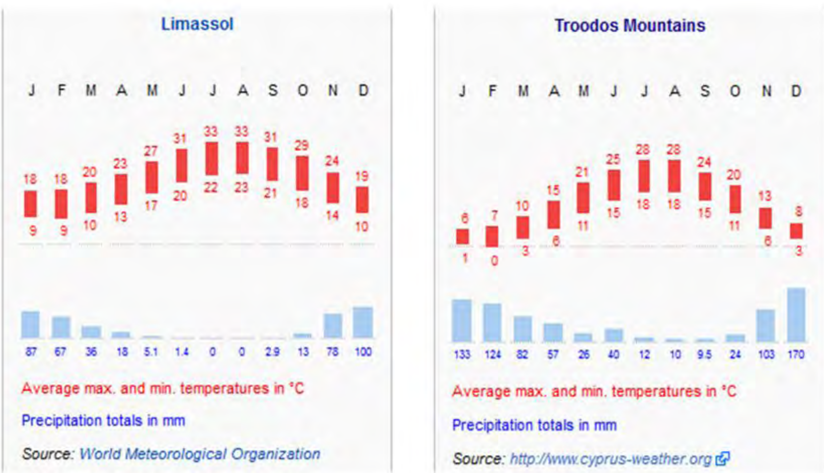

Figure 2.2: Monthly average minimum and maximum temperature and precipitation height in Limassol and Troodos Mountain (adapted from www.wikipedia.org).

2.2 Database

The data were collected based on the needs of the rainfall-runoff model i.e. daily time series of precipitation, temperature and observed runoff. As seen on Figure 2.1 the two gauging stations were weighted using Thiessen polygon area averaging method [Thiessen, 1911] in order to estimate the areal precipitation of the catchment. Minimum and maximum daily values of areal temperature were provided. The mean daily temperature was calculated in order to be used for further analysis. The observed runoff data corresponds to the outlet of the basin. As potential evapotranspiration values were needed, they were estimated through Thornthwaite method [Thornthwaite, 1948]. All the aforementioned time series correspond to 11 consecutive years from 1/10/1986 up to 30/09/1997.

Figure 2.3 shows the time series that were mentioned before, where the mean is also illustrated (red dashed line). Table 2.1 contains basic characteristics of the time series i.e. the mean, the median (Q_{50}), as well as the extreme values of the time series. The catchment could be characterised as rather semi-arid, as the precipitation and observed runoff series indicate. There are some distinctive and probably severe dry periods i.e. 1990-1992 and 1996-1997 that are present both in precipitation and observed runoff time series. Even though temperature time series follows a clear seasonal pattern with no significant fluctuation, precipitation and observed runoff series contain an important amount zero values and present sharp peaks. This is also validated by comparing the mean and the median of the variable. What should be investigated is whether this number of consecutive zeros can be considered as a drought event. Figure 2.4 that illustrates the quantile plot of the precipitation and observed runoff time series reveals that there is an extended problem concerning zero or very low values in the variables. These could be proved to be rather troublesome for the analysis. It is discussed thoroughly further in the study.

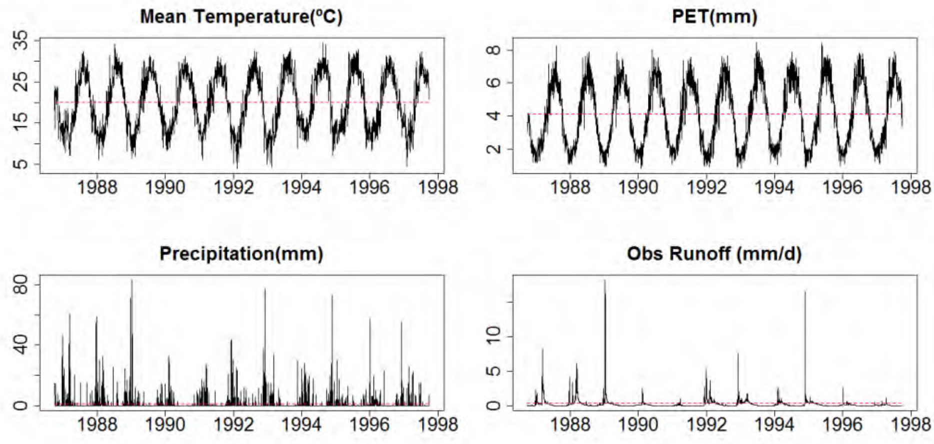

Figure 2.3: Dataset initial time series from 1/10/86 to 30/09/97. Red line indicates the mean value.

Table 2.1: Basic characteristics of the dataset time series

	Mean	Median (Q50)	Max	Min
Mean Temperature	20.05	20.00	34.50	4.00
PET(mm)	4.11	4.05	8.44	0.82
Precipitation (mm)	1.59	0.00	85.25	0.00
Qobs (mm/day)	0.22	0.045	18.15	0.00

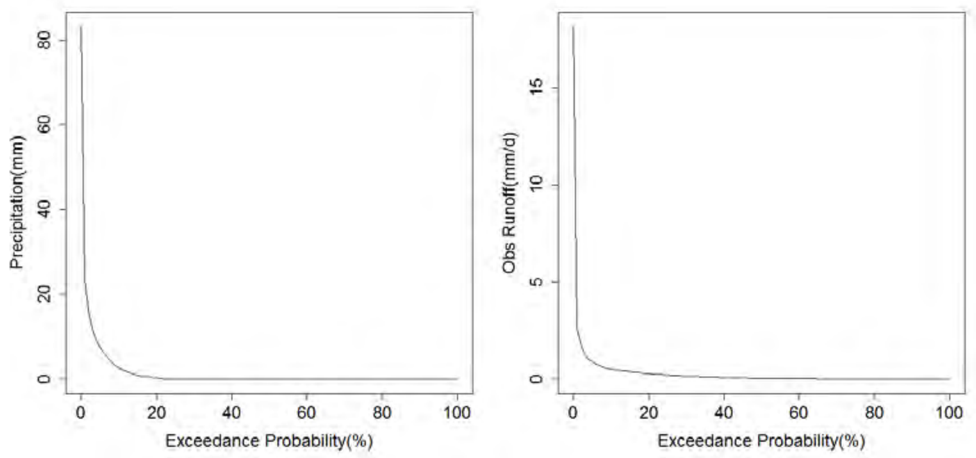

Figure 2.4: Quantile plot of the precipitation and observed runoff time series.

3 METHODOLOGY

This chapter describes the methods as well as the underlying theory that concern the study. Specifically the rainfall-runoff modelling, the post- processing of the data in order to identify and distinguish drought incidents as well as the necessary actions in order to proceed in the qualitative and quantitative analysis of the drought events, are presented. Also, the probabilistic analysis approaches as well as the tools that were used to select and fit theoretical distributions in the sample are being discussed.

3.1 Potential evapotranspiration estimation

The potential evapotranspiration values that were needed in the model were estimated through the Thornthwaite [Thornthwaite, 1948] as seen on the equations below:

$$PET = 16 * \left(\frac{10T_i}{I}\right)^{\alpha} \left(\frac{L}{12}\right)\left(\frac{N}{30}\right) \quad (3\text{-}1)$$

$$I = \sum_{i=1}^{12} \left(\frac{T_{ai}}{5}\right)^{1.514} \quad (3\text{-}2)$$

$$\alpha = (492390 + 17920I - 771I^2 + 0.675I^3) * 10^{-6} \quad (3\text{-}3)$$

where, T_i is the mean daily temperature [°C],T_{ai} is the twelve monthly mean temperatures, L is the mean daily sunshine in hours and N is the number of days in the month being calculated. The main advantage of this method is that only the temperature information is needed beside the sunshine hours that can be defined by the geographic coordinates of the basin. Generally, it is known that the Thornthwaite method gives the underestimate in the arid area while the overestimate in the humid area, respectively [Alkaeed et al., 2006].

3.2 Rainfall-Runoff modelling

Rainfall-runoff models are important and necessary tools for water and environmental resources management. Demands from society on the predictive capabilities of such models are becoming higher and higher, leading to the need of testing and improving existing models and even of developing new theories. There are several types of models that can be classified into three categories: empirical models (black-box models); Conceptual models; physically based models. In order that the model could cope and adapt to any changes that affect hydrological (e.g. floods) and environmental (e.g. water quality) functioning, needs to contain an adequate description of the dominant physical processes. The main benefit of modelling is that can compensate the lack of observational data of drought-related variables and insufficiently record or quality of data [Tallaksen and Van Lanen, 2004]. It should be noted that the application of models specifically to low-flow situations has been relatively limited [Smakhtin, 2001].

Conceptual models form by far the largest group of hydrological models that have been developed and are most often applied in practice, among them is also the HBV model [Bergstrom, 1992]. Most conceptual models are spatially lumped, neglecting the spatial variability of the state variables and parameters. To improve the potential of making use of spatially distributed data, some lumped conceptual models have been extended to be distributed or semi-distributed. Examples are the HBV-96 model [Lindstrom, 1997] and TOPMODEL [Beven, 1995]. The disadvantage of this type of models, however, is that they either lack physical meaning or cannot be measured in the field. Parameter identifiability and equifinality are the major concerns of such models [Zhang, 2005].

3.2.1 TUWmodel

The model used in the study is TUWmodel [Parajka et al., 2013] in R environment that is a conceptual rainfall-runoff model following the structure of the HBV model. The model normally runs on daily values of rainfall and air temperature (to estimate the snow components), and daily or monthly estimates of potential evaporation in a lumped or a semi-lumped way. The HBV model was much used for flood forecasting in the Nordic countries, and many other purposes, such as spillway design floods simulation [Bergstrom, 1992], water resources evaluation (for example Jutman, 1992), nutrient load estimates [Arheimer, 1998] as well as drought analysis [Vrochidou, 2013]. The model estimates the runoff and distinguishes it in quick, intermediate and slow runoff, can separate rain and snow precipitation and also estimates relative soil moisture and actual evapotranspiration values. It should be noted that in the study the model was executed both as lumped and semi-lumped in different scenarios and that the snow routine was not taken into consideration as there was no snow indication in the selected area neither by the measurements nor by the simulation.

The model consists of four subroutines, a subroutine for snow accumulation and snowmelt based on the degree-day approach, a soil moisture accounting procedure to update the soil water, the runoff generation routine and a flow-routing procedure consisting of a simple filter with triangular distribution of weights.

The soil moisture accounting routine, which is controlled by three parameters, computes an index of the wetness and soil moisture storage in a catchment. Parameter FC is the maximum soil storage capacity in the basin and parameter BETA determines the relative contribution to runoff from a millimeter of rain or snowmelt at a given soil moisture deficit while parameter LP controls the shape of the reduction curve for potential evapotranspiration. The runoff generation routine transforms excess water from the soil moisture routine to discharge to each sub-basin and it consists of one upper, non-linear and one lower, linear reservoir connected in series by constant percolation rate (cperc). These are the origin of the quick and slow runoff components of the hydrograph. Flow of water from these reservoirs into runoff is governed by the linear storage coefficient (k0, k1, k2) and overflow from the upper storage based upon exceedance of the threshold storage volume lsuz. Computed outflow from a catchment is transformed using a triangular weighting function, the base width of which is the calibration parameter bmax and cr is the scaling parameter. Table 3.1 present the parameters and the typical range of values. The initial conditions that the model uses are: SSM0 soil moisture (mm); SWE0 snow water equivalent (mm); SUZ0 initial value for fast (upper zone) response storage (mm); SLZ0 initial value for slow (lower zone) response storage (mm). A short review concerning the basic equations used in the model, as explained from Parajka et al. [2007], is shown in Appendix B.

Table 3.1: TUWmodel Parameters.

	Parameter	Description	Typical values
Snow Routine	SCF	snow correction factor	(0.9-1.5)
	DDF	degree day factor	(0.0-5.0 mm/degC/day)
	Tr	threshold temperature above which precipitation is rain	(1.0-3.0 degC)
	Ts	threshold temperature below which precipitation is snow	(-3.0-1.0 degC)
	Tm	threshold temperature above which melt starts	(-2.0-2.0 degC)
Soil routine	LP	parameter related to the limit for potential evaporation	(0.0-1.0)
	FC	field capacity, i.e., max soil moisture storage	(0-600 mm)
	BETA	the nonlinear parameter for runoff production	(0.0-20.0)
	cperc	constant percolation rate	(0.0-8.0 mm/day)
Response function	k0	storage coefficient for very fast	(0.0-2.0 days)
	k1	storage coefficient for fast response	(2.0-30.0 days)
	k2	storage coefficient for slow response	(30.0-250.0 days)
	lsuz	threshold storage state, i.e., the very fast response start if exceeded	(1.0-100.0 mm)
Routing Routine	bmax	maximum base at low flows	(0.0-30.0 day)
	cr	free scaling parameter	(0.0-50.0 day^2/mm)

3.2.2 Calibration and Validation of the model

Concerning the calibration and validation, the model was calibrated for the period 1986-1991 and validated against observed flow for the period 1992 -1997 in order to establish calibration reliability. The R version of the model does not have any restrictions concerning the optimisation function. For this study the square root Nash-Sutcliffe efficiency [Bengtsson, 2005], as seen on equation 3-4:

$$NSE_{\sqrt{Q}} = 1 - \frac{\sum_{i=1}^{n}(\sqrt{Qobs_i} - \sqrt{Qsim_i})^2}{\sum_{i=1}^{n}(\sqrt{Qobs_i} - \overline{\sqrt{Qobs_i}})^2} \quad (3\text{-}4)$$

where, Q_{obs} is the observed flow; Q_{sim} the simulated flow and $\overline{Q_{obs}}$ is the average observed flow over the certain period. The square root transformation of the flow values leads to the flattening of peaks and the low flows are kept more or less at the same level. As a result the influence of the low flow values is increased in comparison to the flood peaks resulting in an increase in sensitivity, similarly to the logarithmic transformation [Krause et al., 2005].

The calibration of the model was performed automatically using a minimising optimization technique to improve the efficiency of the model. Specifically the second factor of equation 3-2 was minimised through the Self-Organising Migrating Algorithm (SOMA). The Self-Organising Migrating Algorithm [Zelinka, 2004] is a general-purpose, stochastic optimisation algorithm. The approach is similar to that of genetic algorithms, although it is based on the idea of a series of migrations by a fixed set of individuals, rather than the development of successive generations. It can be applied to any cost-minimisation problem with a bounded parameter space, and is robust to local minima.

3.2.3 Lumped and Semi-Lumped simulation of the model

As mentioned before the simulation was performed with a lumped as well as with the semi lumped version of the model. The lumped simulation was performed in the whole Yermasoyia catchment with the dataset that was mentioned in Chapter 2. Concerning the semi-lumped model the catchment was divided into different zones based on the elevation. The semi-lumped model calculates one set of parameters to simulate the variables in the different zones. Dividing the catchment into different zones could be very practical in order to localise any drought events and to be able to identify what component affects most the drought generating mechanism. In this study three different simulations were performed i.e. a lumped model simulation that concerns the basin as a whole, a semi-lumped simulation with two elevation zones and one with four elevation zones.

Figure 3.1 presents the subdivision of the catchment for the semi-lumped model in two elevation zones (a) and in four elevation zones (b) and the area of each zone respectively. The rainfall data were weighted based on the area of each zone and were adjusted by a daily precipitation gradient based on the mean elevation of each zone in order to be imported on the model. Apart from the definition of the zone's area all the other input variables (areal temperature, potential evapotranspiration and observed runoff values) were not adjusted.

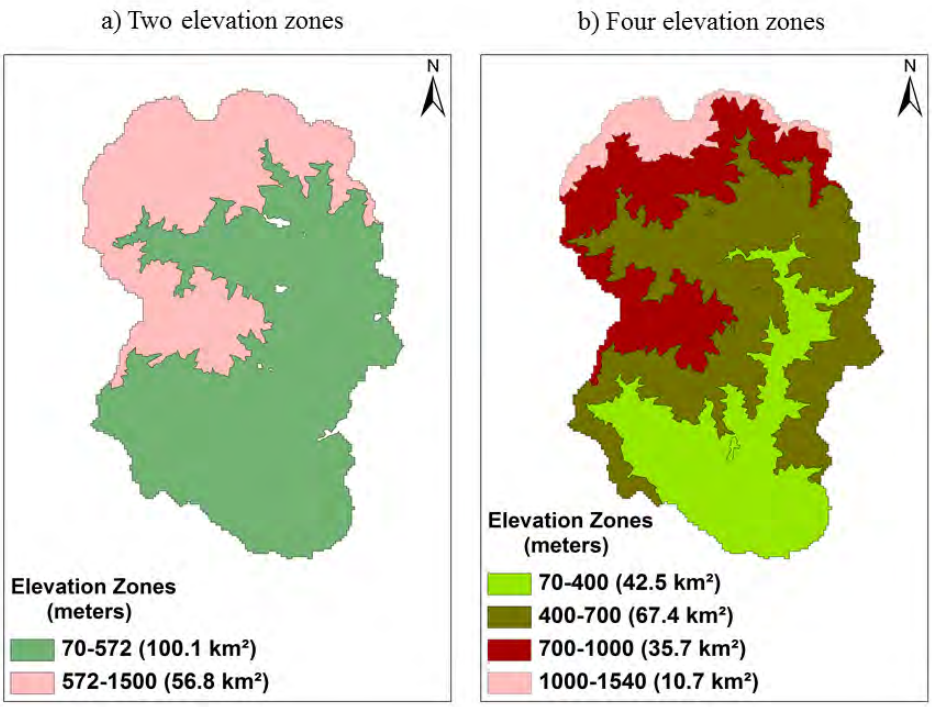

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Figure 3.1: Elevation zones for the semi-lumped model in two elevation zones (a) and in four elevation zones (b). The area of each zone is also presented.

3.3 Drought Identification with Threshold Level Method

As this study is mostly concerned by hydrological droughts the suitable and commonly used method in order to identify the drought events is the threshold level method. Yevjevich [1967] proposed the theory for identifying drought parameters and investigating their statistical properties: (a) duration, (b) severity, and (c) intensity. The most basic element for deriving these parameters is the truncation or threshold level, which may be a constant or a function of time. A drought event starts when the variable falls below the selected threshold level and the event continues until the variable exceeds the threshold; that defines the duration of the event. For variables like precipitation and discharge, the most commonly used severity measure is the deficit volume. The deficit volume is calculated by summing up the differences between the variable and the threshold level over the period that the variable is below the threshold. The aforementioned characteristics i.e. the drought duration, the deficit volume as well as the number of drought events can be used as the main identifiers for drought analysis.

The selection of the threshold level is the most crucial parameter. As the threshold level is depended on the objective of the study (operational or research purposes).

Also, the threshold could be either fixed or varying (daily or monthly) as it is illustrated in Figure 3.2. It should be taken into consideration that unusual low flows during high flow seasons might be important for later drought development. However, periods with relatively low flow either during the high flow season or for instance due to a delayed onset of a snowmelt flood, are commonly not considered a drought.

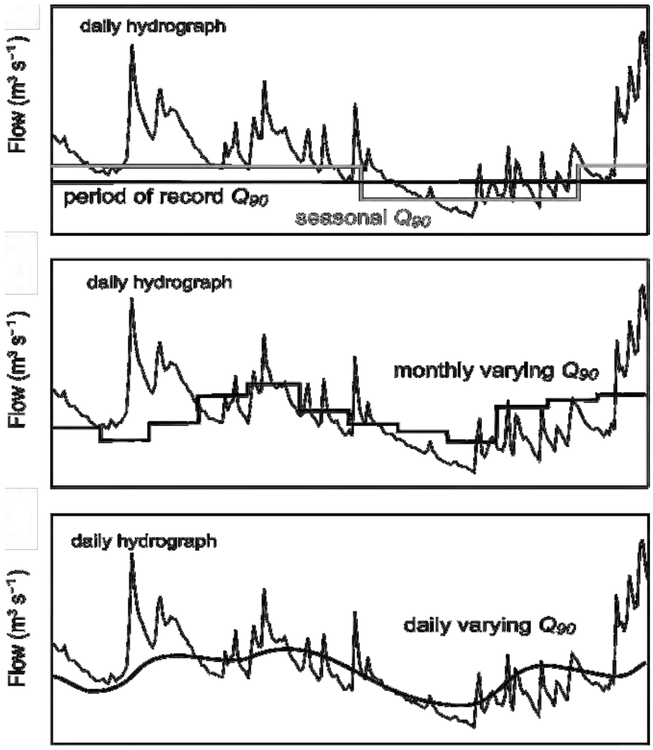

Figure 3.2: Illustration of threshold levels: fixed threshold (top); monthly varying threshold (middle); daily varying threshold (bottom) (adapted from WMO, 2008)

In this study a monthly varying threshold was selected. In semi-arid catchments, like in this case, a short time scale threshold seems to be most appropriate. However the time series record is not sufficiently long (11 consecutive years) to support a reliable daily varying threshold. The important advantage of a monthly varying threshold against a fixed, in our case, is that it can distinguish which events can be characterised as droughts (deviating from the normal conditions) especially in the dry summer season (Figure 2.3). Summer, in our case study, is dry so it is not possible to definitely distinguish any deviation from the normal conditions. On the contrary a fixed threshold would return much longer events as it would take into account all the dry periods. As mentioned before the threshold is depended not only on the objective of the study but is a user defined parameter, so it can be assumed that the later scenario would be less probable as it indicates an area with extensive water resources problem. A variable threshold level was also used by e.g. Stahl [2001], Vidal et al. [2010], Hannaford et al. [2011] and Parry et al. [2012].

The selection of the threshold level for the selected area and dataset of the study proved to be quiet challenging to derive. As mentioned before the area is semi-arid and the time series of the data set contain a significant amount of zeros (in some cases almost the 80 percent of the values are zeros), so a different approach should be made. The zero values were removed from the original time series creating new non-zero time series where the 50th quantile (Q_{50}) was estimated [WMO, 1986]. The estimated median values were then linked to the corresponding quantile of the original time series based on the flow duration curves of the samples (Figure 3.3 is an example of the connection between the original and the non-zero rainfall time series). Table 3.2 shows the estimated Q_{50} quantiles in the non-zero time series and the linked relationship to the original time series. No appropriate threshold was found for the quick runoff time series as the calculated median form the original time series corresponded to lower than 1 percent exceedance probability.

It should by mentioned that deriving the threshold level from non-zero time series implies the assumption that consecutive zero values are not considered as drought events. That most likely is the case in the selected area what needs to be defined is if the assumption is valid in all of the cases or in the majority of them. The mean of monthly threshold levels were calculated and compared to median of the non-zero time series; the absolute differences do not exceed 10 percent.

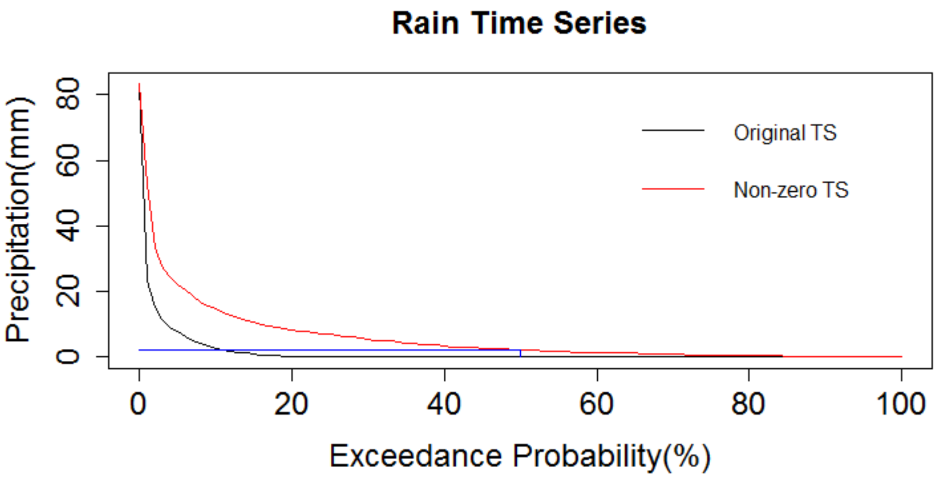

Figure 3.3: Flow duration curves for the original and non-zero rainfall time series. The Q50 of the non-zero time series corresponds to Q15 in the original time series.

Table 3.2: The relationships between the median of the non-zero and the original time series.

Time series	Q50 (non-zero time series)	Corresponding quantile in the original time series (%)
Rain (mm)	2.16	15
Sim. Runoff (mm/d)	0.35	20
Quick Runoff (mm/d)	1.71	0.11
Intermediate Runoff (mm/d)	0.65	15
Slow Runoff (mm/d)	0.32	18
Soil moisture (mm)	16.53	36

3.3.1 Pooling minor droughts

Pooling procedures as they are mentioned by WMO [2008] include the moving average procedure (MA), the inter-event time (IT) and the inter-event time and volume criterion (IC). The MA procedure filters the time series applying a moving average method. This is illustrated in Figure 3.4, where a 10-day averaging interval has been used. A study by Fleig et al. [2006] found that the MA procedure is applicable to both quickly and slowly responding streams. The averaging interval can easily be optimized, and a filter width of around 7 days is appropriate for many hydrological regimes. An additional advantage of the MA pooling method is that it reduces the problem of minor deficits. A drawback is that the method modifies the discharge series and might introduce dependency between the deficit events, particularly for long moving averages.

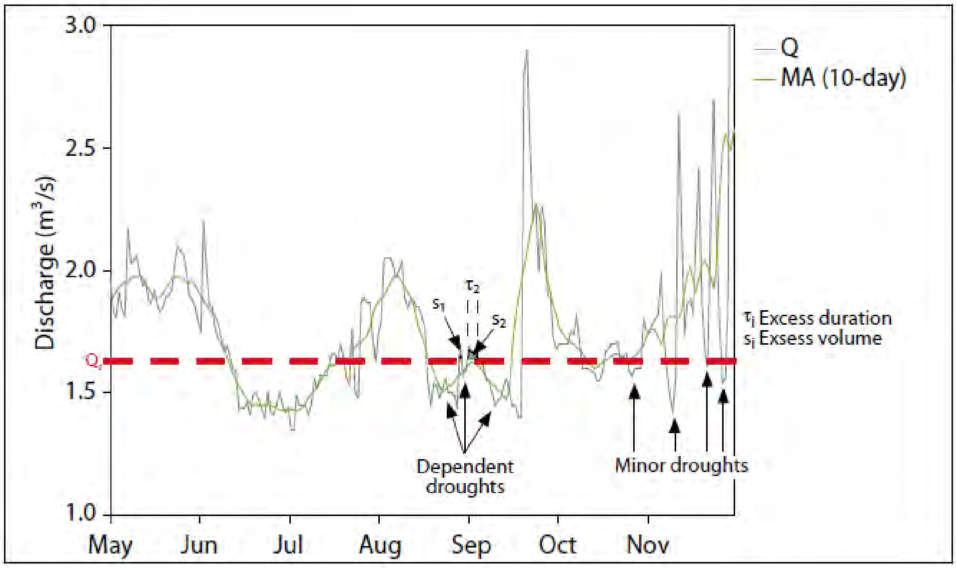

Figure 3.4: Illustration of pooling dependent deficits and removal of minor deficits by an MA(10-day) filter (adapted from WMO, 2008)

The inter-event time method pools dependent deficits with characteristics (d_i in days, v_i in millimetres) and (d_{i+1}, v_{i+1}) if they occur less than a predefined number of days, t_{min}, apart. The pooled duration and deficit volume can be defined as:

$$d_{pool} = d_i + d_{i+1} \tag{3-5}$$

$$v_{pool} = v_i + v_{i+1} \tag{3-6}$$

Tallaksen et al. [1997] introduce the IC method, where two events are pooled if: (a) they occur less than a predefined number of days, t_{min}, apart (the inter-event time (τ_i) is less than t_{min}) and; (b) the ratio between the inter-event excess volume (s_i) and the preceding deficit volume, v_i, is less than a critical ratio, p_i. The adjacent deficits are then pooled if the aforementioned requirements are fulfilled. The pooled deficit characteristics can be calculated as follows:

$$d_{pool} = d_i + d_{i+1} + \tau_i \tag{3-7}$$

$$v_{pool} = v_i + v_{i+1} - s_i \tag{3-8}$$

The method was tested on two rivers with contrasting flow regimes and it was found that the optimal values of the pooling criteria were $t_{min} = 5$ days and $p_i = 0.1$.

In the study the IC pooling method was used in the time series of interest i.e. the runoff time series as well as all of the components that were simulated, the soil moisture time series and the rainfall time series. As one of the goals of the study is to investigate the lag between drought events occurrences for different variables it was practical to eliminate minor drought events that add additional noise to the analysis, in order to identify the main characteristics of the phenomenon. The IC method was preferred to IT method as the additional volume criterion returns more reliable results. The parameters selected are the same with the optimal values that mentioned before ($t_{min} = 5$ days and $p_i = 0.1$) as they eliminate the problem of having short duration drought incidents (most of the short duration events in this study were from 1 up to 3 days).

3.3.2 Drought events analysis

As the threshold level is defined for each time series and the pooling method is completed we can proceed to the analysis of the drought events that have been estimated. Analytical tables containing information that concern the events such as, the duration, the start and end date of the event as well as the volume of the deficit have been formed. The duration and the start date of the event were used in order to create new time series that contain the information as a binary signal {0, 1}. Where, an event of specific duration is represented by the same number of consecutive “1” and “0” stands for the days with no drought events. The transformation that was performed is practical for the qualitative analysis as it is the most effective way to study the propagation of droughts without the interference of scale discrepancies that have might occurred if the events have been plotted versus the corresponding volume.

The scope of the qualitative analysis is to investigate the lag time of drought event occurrences between the different components using a signal cross-correlation analysis. For that purpose Pearson’s linear correlation coefficient (r) was used and can be calculated by the following equation:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{(n-1)s_x s_y} \tag{3-9}$$

where, $\bar{y}$ and $\bar{x}$ are the sample means of x and y, and s_x and s_y are the sample standard deviations of x and y. The procedure in order to define the lag, which is schematically represented at Figure 3.5, is as follows: the time series of interest (Variable A) is shifted on a daily time scale; for each shift the Pearson’s linear correlation coefficient is calculated between the two selected variables. The main idea is that when the pulses of the two time series concur there will be a higher value of linear correlation in the certain lag than in the rest. That lag is considered as the characteristic delay of event occurrence between the two variables.

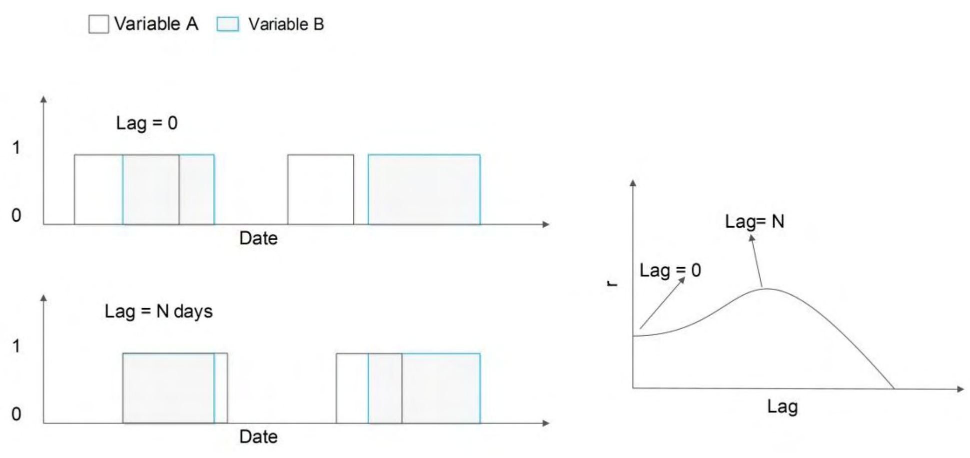

Figure 3.5: Schematic representation of the cross-correlation lag identification procedure.

Apart from the correlation analysis that concerns the whole time series, an event to event analysis was also performed. Specifically, the centroid points of the drought events were identified and the lag of occurrence was derived based on the centre points (figure 3.6). The results are presented further (Chapter 4) in histogram plots. It should be noted that both the cross-correlation and the event to event analysis, were performed comparing rain drought events time series to the rest of the variables (Table 3.2) and likewise for the soil moisture.

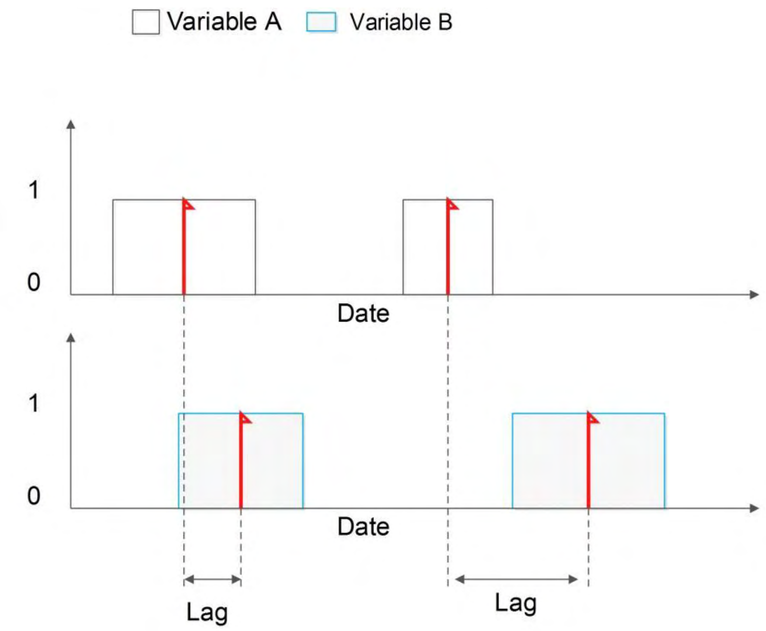

Figure 3.6: Schematic representation of the event to event lag identification procedure.

3.4 Classification of hydrological droughts

Based on the drought generating mechanisms that have been analysed and the propagation principles that define the elements of the hydrological cycle the hydrological droughts can be distinguished in six main categories as proposed by Van Loon et al, 2012. The proposed drought typology that is based on governing drought propagation processes was derived from catchment-scale drought analysis. The processes underlying these drought types are the result of the interplay of temperature and precipitation at catchment scale in different seasons. The drought typology is transferable to other catchments, including outside Europe, because it is generic and based upon processes that occur around the world. Knowing the typology of drought events and especially the typology of the severe events is practical information that can be used by decision makers especially in water management applications.

The categories are defined as follows: Classical rainfall deficit droughts; rain-to-snow-season drought; wet-to-dry-season droughts; cold snow season droughts; warm snow season droughts and composite drought. In this study as there are no snow observations in the selected area only classical rainfall deficit droughts, wet-to-dry-season droughts and composite droughts are being investigated. The classical rainfall deficit drought is caused by lack of rainfall (meteorological drought) that propagates and develops into a hydrological drought. The wet-to-dry-season droughts are mainly caused by a rise in temperature or in potential evapotranspiration. They are identified by being in the dry season (in this case mainly in the summer) and there are is no corresponding meteorological drought event. A composite drought combines different drought generating mechanisms. The main feature of the composite drought is that the system has not yet recovered from a hydrological drought event when the next event starts [Van Loon et al, 2012]. In this study composite drought events have excessive long duration. Figure 3.7 illustrate examples of classical rainfall deficit and wet-to-dry-season drought events and figure 3.8 an example of a composite deficit event with long duration.

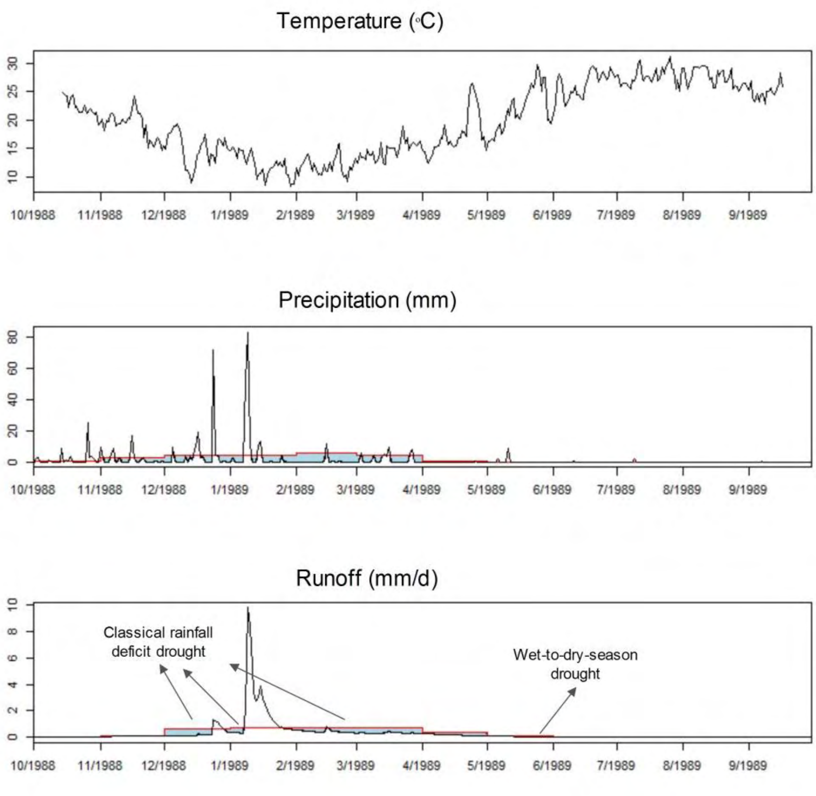

Figure 3.7: Example of classical rainfall deficit and wet-to-dry-season drought events (1988-1989)

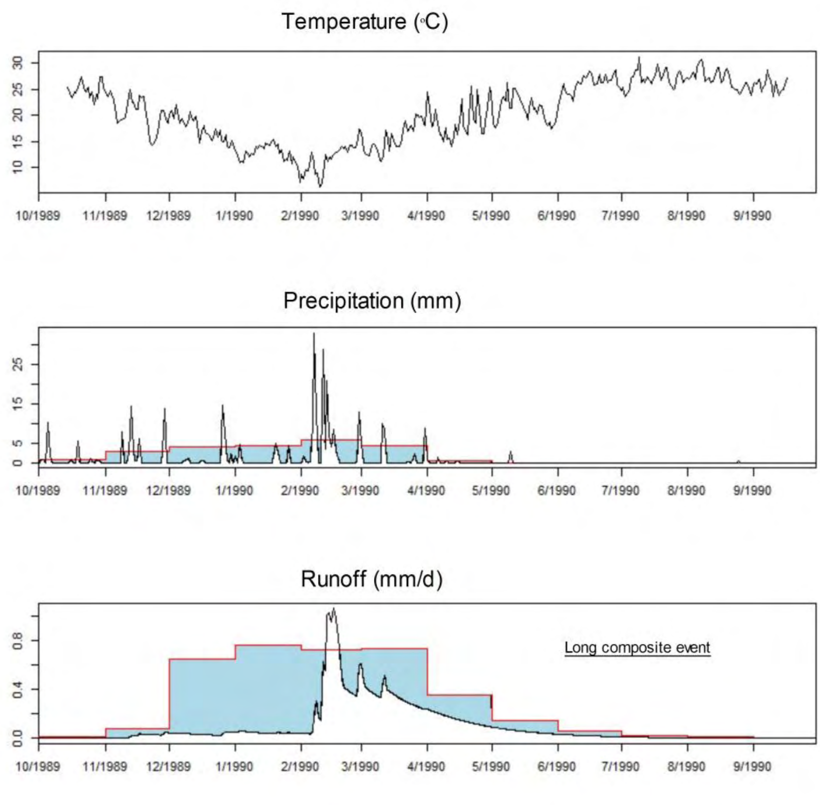

Figure 3.8: Example of composite drought event (1989-1990)

3.5 Probabilistic analysis

The probabilistic analysis was performed on volume deficit annual maxima time series, as they were extracted using selected monthly thresholds, with the use of Hydrognomon software [Hydrognomon]. Hydrognomon is a free software application suitable for the process and analysis of hydrological time series. Its main functions includes statistical analysis, regression and infilling of time series, tests, Intensity Duration Frequency curves, stage-discharge curves construction and calculations, hydrometry, hydrological simulation of water basins, evaporation and evapotranspiration calculations, etc. Specifically, the tools for statistical analysis include features such as distribution functions fitting, multi regression analysis, statistical forecasting (return levels estimation), and Monte Carlo simulations. Hydrognomon is part of the openmeteo.org framework and has been developed mainly to serve the research activities of the ITIA research group (http://www.itia.ntua.gr) which is responsible for the design and maintenance of the software.

The software calculates the empirical cumulative distribution functions of the time series based on the equation that follows (Weibull approximation):

$$\frac{i}{n+1} \tag{3-10}$$

where, *i* is the rank of the specific value and n is the size of the sample.

Concerning the fitting of the distribution and the estimation of the parameters the L-Moments method [Hosking, 1990] was used. The L-Moments are a linear function of probability weighted moments. Hosking showed that the first few L-Moments follow the probability weighted moments (equations (3-11) up to (3-14)),where β_0, β_1, β_2, β_3, correspond to the specific order of the probability weighted moments, λ_1 is the sample mean and λ_2 the data dispersion. The L-Moment ratios stand as a measure of the L-skewness, L-kurtosis and L-CV (coefficient of variation). Specifically, L-CV is defined as the ratio of the second to the first L-moment, L-skewness as the ratio of the third to the second L-moment and L-kurtosis as the ratio of the fourth to the second L-moment.

$$\lambda_1 = \beta_0 \tag{3-11}$$

$$\lambda_2 = 2\beta_1-\beta_0 \tag{3-12}$$

$$\lambda_3 = 6\beta_2-6\beta_1+\beta_0 \tag{3-13}$$

$$\lambda_4 = 20\beta_3-30\beta_2+12\beta_1-\beta_0 \tag{3-14}$$

The evaluation of the goodness of fit of the distribution was derived by Kolmogorov–Smirnov test [Massey, 1951]. The Kolmogorov–Smirnov test is a non-parametric test for the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution. The Kolmogorov–Smirnov statistic quantifies a distance between the empirical distribution function of the sample and the cumulative distribution function of the reference distribution and compares it with a critical value obtained from reference tables. The software estimates the achieved significance level (α) and the maximum distance between the two distributions (D_{max}). If the estimated significance level is greater than the selected the null hypothesis (i.e. the sample follows the selected distribution) is accepted.

The goal of the probabilistic analysis is to indicate the proper theoretical distribution in order to be able to estimate characteristic features used in design applications, such as the return period or the return level, for time durations that exceed the duration of the sample. Also the using the sample the empirical return levels are estimated and are compared.

4 RESULTS AND DISCUSSION

In this chapter the results of the analysis are illustrated and discussed. Specifically, the evaluation if the model as well as the results of the simulation, the qualitative analysis (lag time identification), the quantitative analysis concerning the severity of the drought events as well as the classification of hydrological drought events and the probabilistic analysis, results are shown. Apart from that the section comments and synthesizes the results that were presented in order to evaluate and summarise the main points of the analysis.

4.1 Calibration and Validation evaluation

The three different simulations that were performed i.e. lumped, semi lumped with 2 elevation zones and semi-lumped with 4 elevation zones, were basically optimised and evaluated using the square root transformation of NSE (equation (3-4)). Three more criteria were added in order to evaluate the model: the proportion runoff volume error (equation (4-1)); the root mean square error between the simulated and the observed value (equation (4-2)) and the coefficient of determination (R squared) which is the square of r, Pearson’s linear correlation coefficient (equation (3-9)). The equations for the estimation of the proportion runoff volume error and root mean square error are given below:

$$\%DV = \frac{Vsim - Vobs}{Vobs} \times 100 \tag{4-1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(Qobs_i - Qsim_i\right)^2}{n}} \tag{4-2}$$

where, V_{sim} is the total estimated volume of the simulated runoff time series, V_{obs} the total estimated volume of the observed runoff time series, Q_{sim} and Q_{obs} the simulated and observed runoff, respectively, and n the size of the sample. Concerning the volume error criterion it should be clarified that negative values indicate underestimation of the observed sample and vice versa for positive values.

Table 4.1 presents the aforementioned criteria as they were estimated for the calibration (1986-1991) and validation period (1992-1997) as well as for the complete record of the time series. It should be noted that the coefficient of determination (R squared) was estimates only for the full record of the time series. In order to calculate the statistic on the semi lumped models the zones where weighted based on the area of each zone. Detailed plots for each zone's simulated flow are presented further in the chapter.

Table 4.1: Evaluation of the models

		NSE(√Q)	NSE	Vol. Error (%)	RMSE
Lumped	Calibration	0.92	0.87	-1.26	0.32
	Validation	0.89	0.82	-6.34	0.32
	Complete record	0.91	0.85	-2.81	0.32
Semi-Lumped (2 zones)	Calibration	0.89	0.86	1.28	0.30
	Validation	0.86	0.79	2.39	0.35
	Complete record	0.89	0.81	3.40	0.34
Semi-Lumped (4 zones)	Calibration	0.88	0.82	-17.21	0.44
	Validation	0.82	0.71	18.58	0.46
	Complete record	0.86	0.78	-16.86	0.45

Also, Figure 4.1 presents the observed and simulated runoff as it was estimated for the three different models i.e. the lumped, the semi lumped with 2 elevation zones and the semi lumped with 4 elevation zones. The plot concerns the total record length (from 1986 to 1997). The estimated parameters of the model and the initial conditions, as they were mentioned in section 3.2.1, are located in Table A1 in Appendix A. Also Figure 4.2 illustrates the flow duration curved for the total runoff from the 3 different simulations.

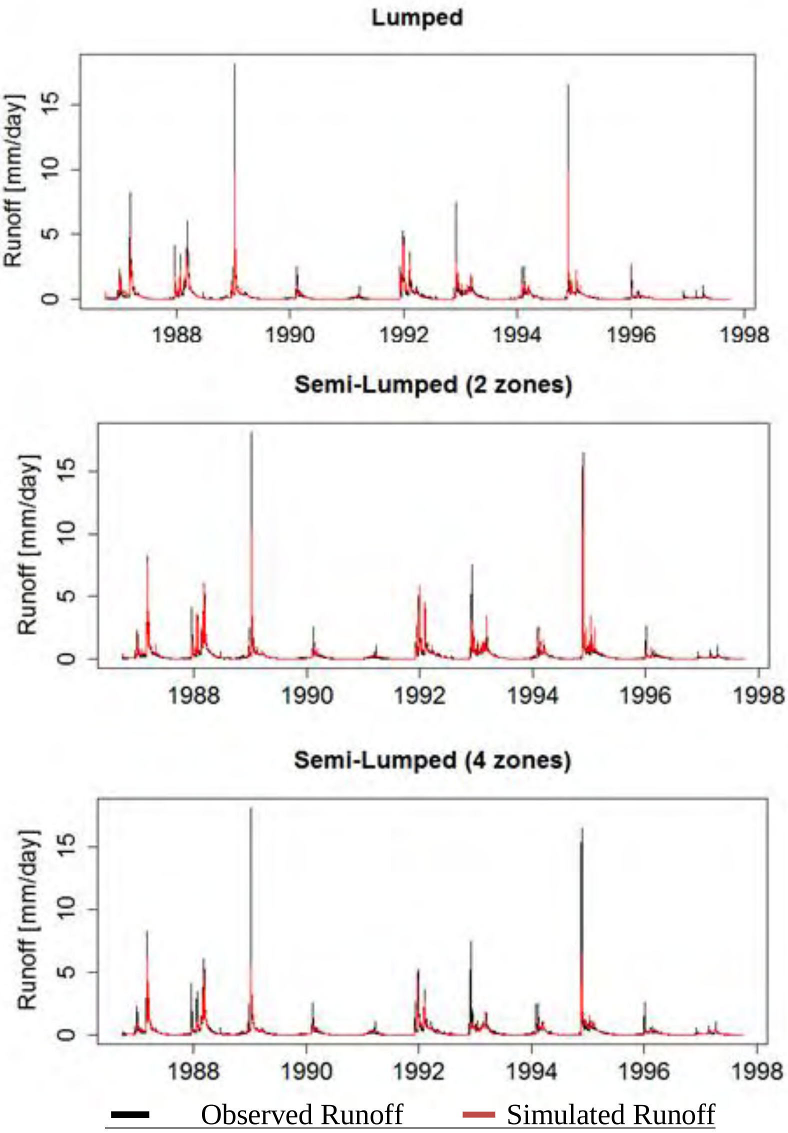

Figure 4.1: Observed and simulated runoff time series for the three different simulations. The plots correspond to the whole record of time series

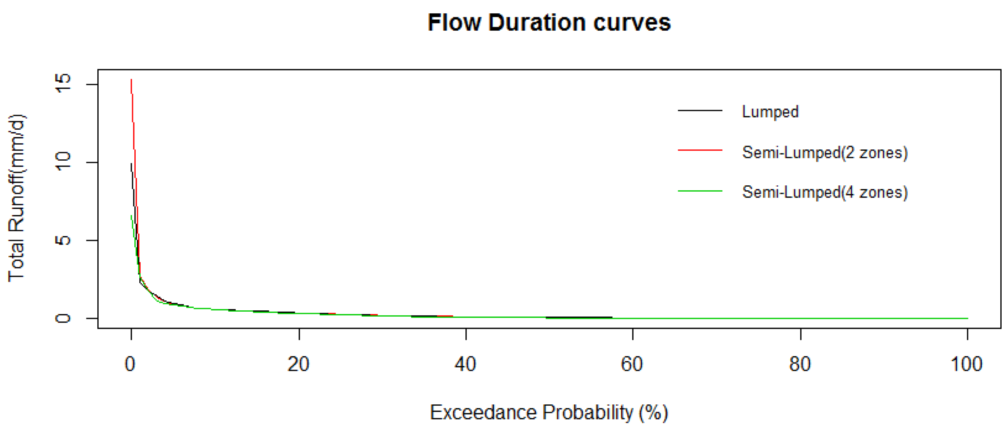

Figure 4.2: Flow duration curves for the total runoff of the three simulations i.e. the lumped and semi-lumped with two and four elevation zones.

4.2 Exported results from the model

The results that were exported concern the variables mentioned in Table 3.2, i.e. the total runoff, the intermediate runoff, the slow runoff and the soil moisture time series. The model estimates each of the aforementioned variables for each zone. Figure 4.3 that follows compares the 3 different simulations of the model. It should be noted that the zones are aggregated based on the area of each zone in order to be comparable with the lumped model.

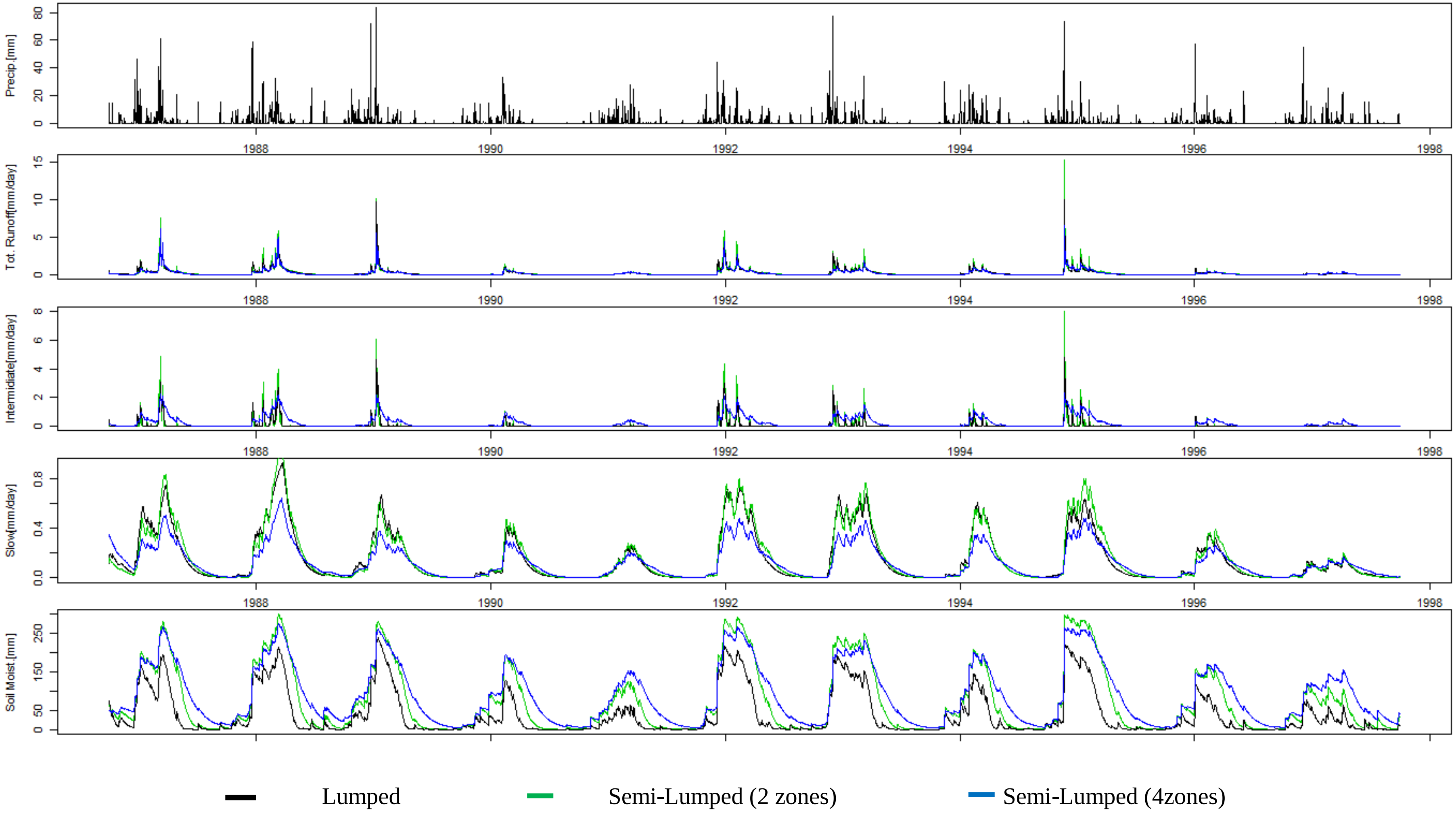

Figure 4.3: Comparison between the different simulations (lumped and semi-lumped with two and four elevation zones).

4.3 Lumped and semi-lumped model discussion

The TUWmodel that was used in the study (which is actually similar to the HBV model) was selected as it can give different response components of the flow and is adequate for the study. The R version of the TUW model that was used has the main advantage of being completely flexible. You can choose between different optimisation functions (e.g. NSE, volume error and correlation coefficient) or you can develop a user based function to calibrate the model. Also there is no pre-set optimisation technique so the user is free to use any procedure in order to calibrate the model and find the optimum se of parameters. One drawback of the certain version was that there was no information concerning the lower ground water storage which could be used in the analysis. In general, the model as well as the selected optimisation function and algorithm seem to perform sufficiently well in both the lumped and semi-lumped version of the model. Manual calibration could return even better results but because of limited time reserve an automated procedure was preferred.

The reason of using a lumped and two semi-lumped versions of the model is not only to check the ability of the model to simulate but it helps the analysis providing us with extra information that a lumped simulation would not. Having two or four elevation zones indicate the effect of altimeter in the drought generating or put it better in the drought delaying mechanism. Also, having several elevation zones can help to isolate the dominant drought inducing zone where the delaying effect between the zones is more evident.

Concerning the simulated results, there are noticeable differences between the lumped and semi-lumped version of the model (Figures 4.1-4.3) but all the simulations represent sufficiently well the observed flow. The fact that the semi-lumped models are scoring lower than the lumped model can be attributed to the lack of spatially distributed data. Only two gauging stations and a precipitation gradient that was derived from the stations were used in the study in order to allocate the rainfall in the zones. Probably a distributed or semi-distributed model that would estimate different parameters for each zone would return better results. The positive thing is that all the models seem to perform well in the low flow generation with no particular differences (Figure 4.3). Based on the statistic on Table 4.1 the lumped version was considered more reliable and selected to be used further in the analysis.

4.3.1 Threshold level selection in semi-arid catchment

In order to derive the threshold level, as explained in Chapter 3, the zero values had to be removed from the time series. This approach implies the assumption that consecutive zero values are not considered as drought events. This is a strong assumption and though it can be supported from a logical point of view, because if all zero values are included in the low flow analysis, it will return large drought events with even greater volume deficits that would most likely diminish any water resources in the area. The assumption needs further investigation from a different aspect that would probably include data from the municipality water agency.

Despite the assumptions that need to be made, it is essential to study semi-arid or drought prone areas like the certain catchment. It should also be mentioned that selecting a varying threshold (monthly or daily) could be very practical in order to avoid considering repeatedly dry summers as constant drought season, like in the case of a fixed threshold, and should be preferred, in my opinion.

4.4 Cross-Correlation analysis

The cross-correlation analysis was performed for the three models and it cross-correlates the rain and soil moisture deficit time series with the rest of the variables as it is explained in chapter 3. Concerning this analysis the peak of the graphs is the most important factor as it indicates the characteristic lag time. It should be noted that the observed runoff time series is also included in the analysis in order to check the simulated results.

4.4.1 Lumped model

Figure 4.4 shows the cross-correlation analysis for the rain deficit time series with the total simulated, intermediate and slow runoff time series. There is a good match between the simulated and observed runoff values.

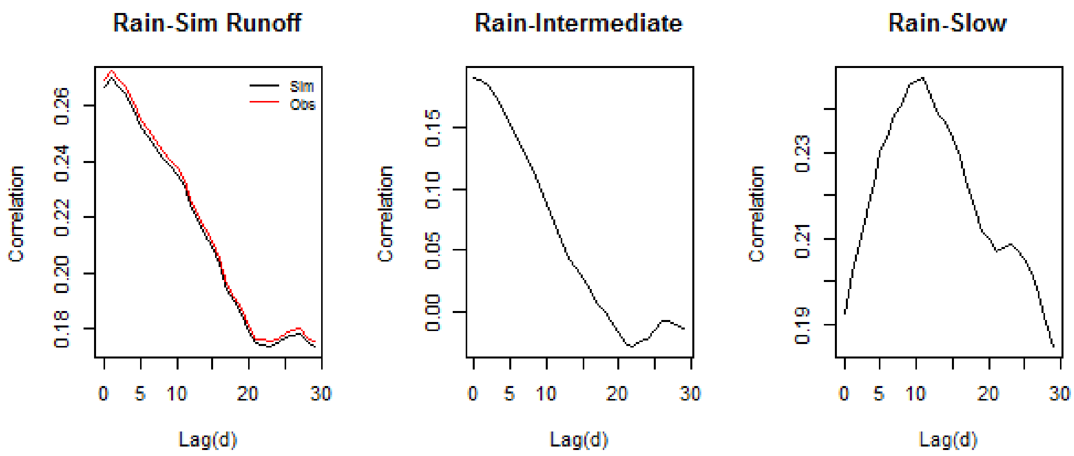

Figure 4.4: Cross-correlation analysis for the rain deficit time series.

Figure 4.5 shows the cross-correlation analysis for the soil moisture deficit time series with rain, simulated and observed, intermediate and slow runoff time series.

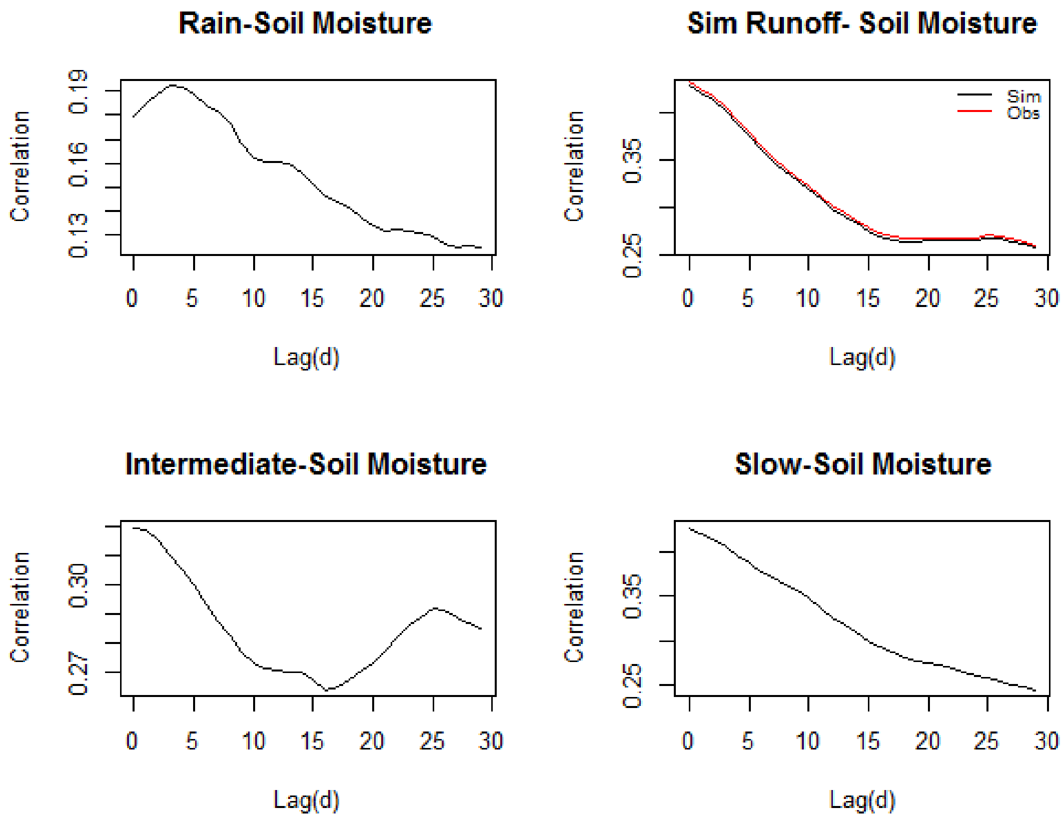

Figure 4.5: Cross-correlation analysis for the soil moisture deficit time series.

4.4.2 Semi-lumped models

In this case where there are multiple time series that concern different zones the correlation was performed with variables that belong to the same zone e.g., the rain deficit time series of the lowest elevation zone was cross-correlated with the simulated runoff that was estimated in that zone and likewise for the other variables. Figure 4.6 and 4.7 illustrate the rain deficit time series cross-correlation analysis for the 2 and 4 zones semi-lumped models, respectively.

The soil moisture cross-correlation analysis is based on the same principles. Figure 4.8 and 4.9 illustrate the soil moisture deficit time series cross-correlation analysis for the semi-lumped models. It should be noted that like the previous section the observed runoff time series is also included and correlated with the aggregated time series (based on the area) in order to check the results.

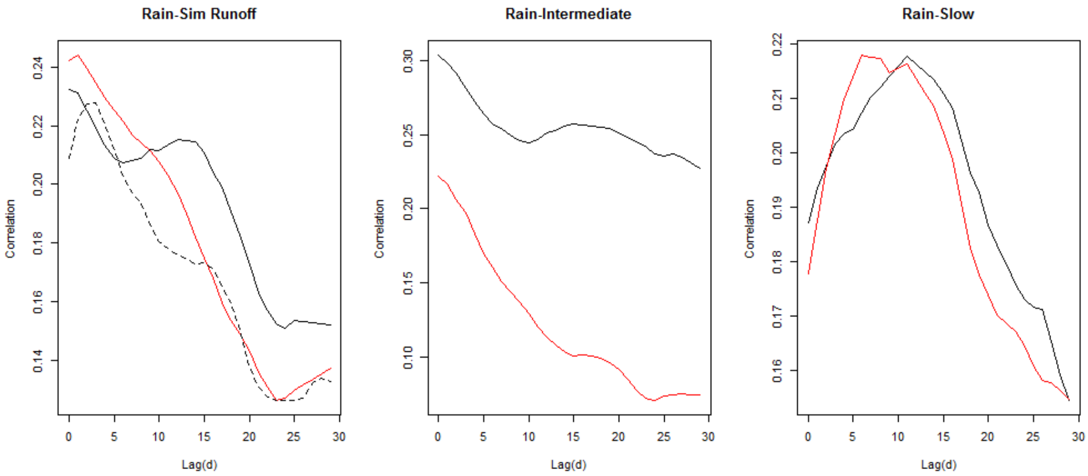

Figure 4.6: Two elevation zones semi-lumped model cross-correlation analysis for the rain deficit time series. Black line illustrates the lower zone and red line the higher elevation zone. The dashed line is the cross-correlation between the aggregated rain and observed runoff time series.

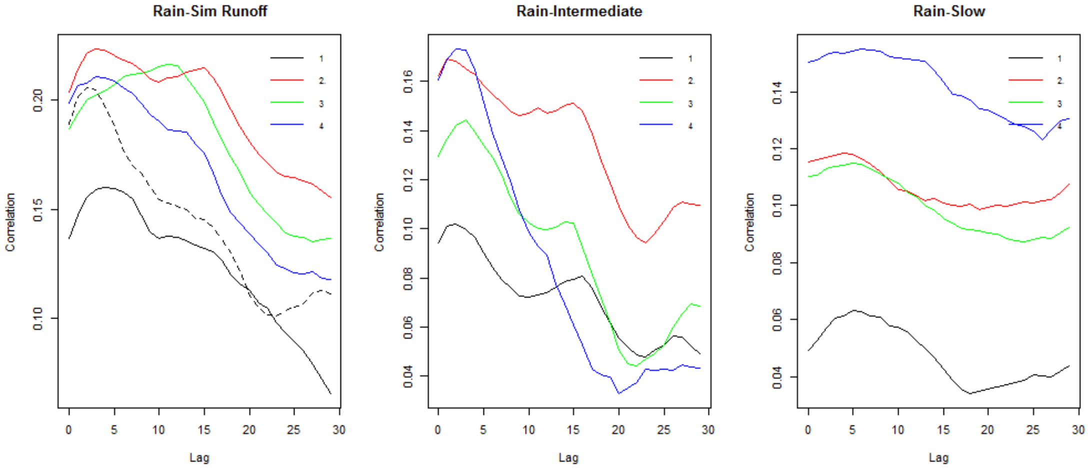

Figure 4.7: Four elevation zones semi-lumped model cross-correlation analysis for the rain deficit time series. Zone 1 always refers to the lowest elevation zone. The dashed line is the cross-correlation between the aggregated rain and observed runoff time series.

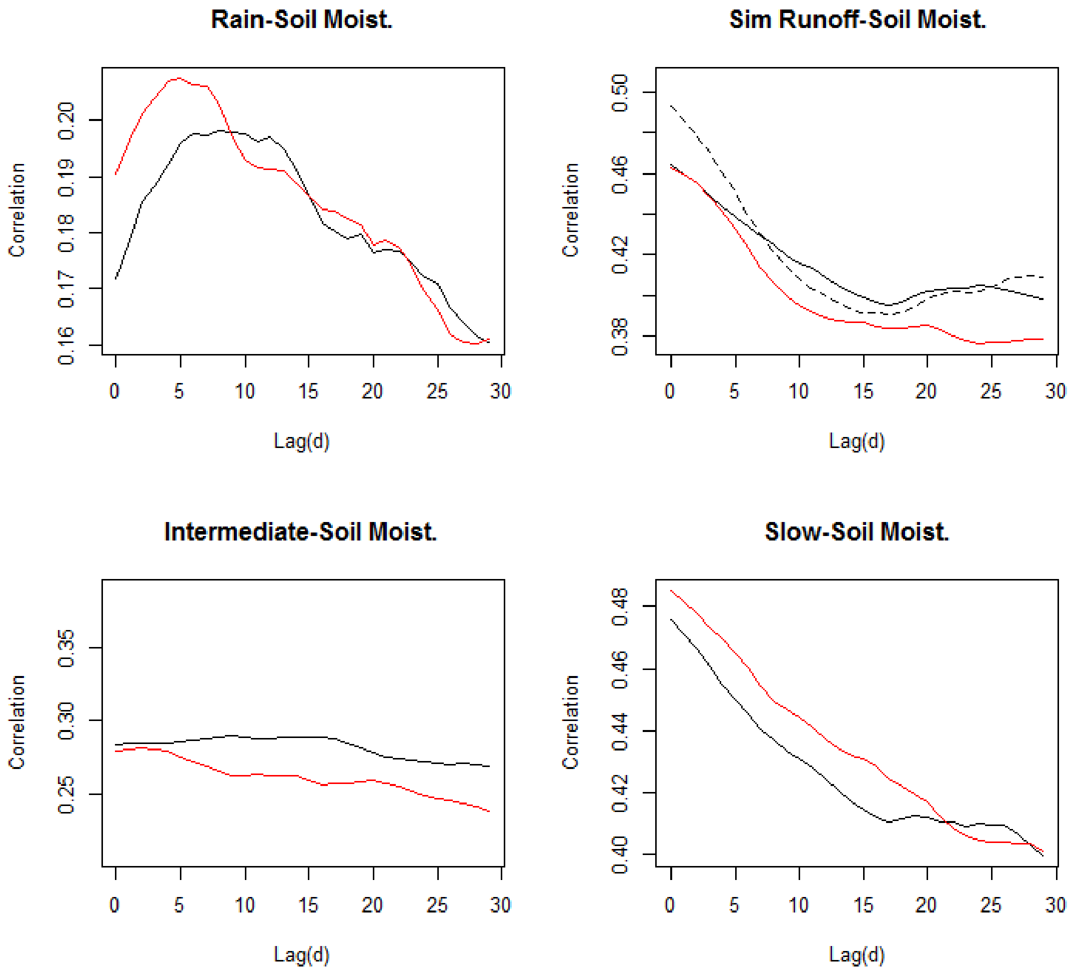

Figure 4.8: Two elevation zones semi-lumped model cross-correlation analysis for the soil moisture deficit time series. Black line illustrates the lowest zone and red line the highest elevation zone. The dashed line is the cross-correlation between the aggregated soil moisture and observed runoff time series.

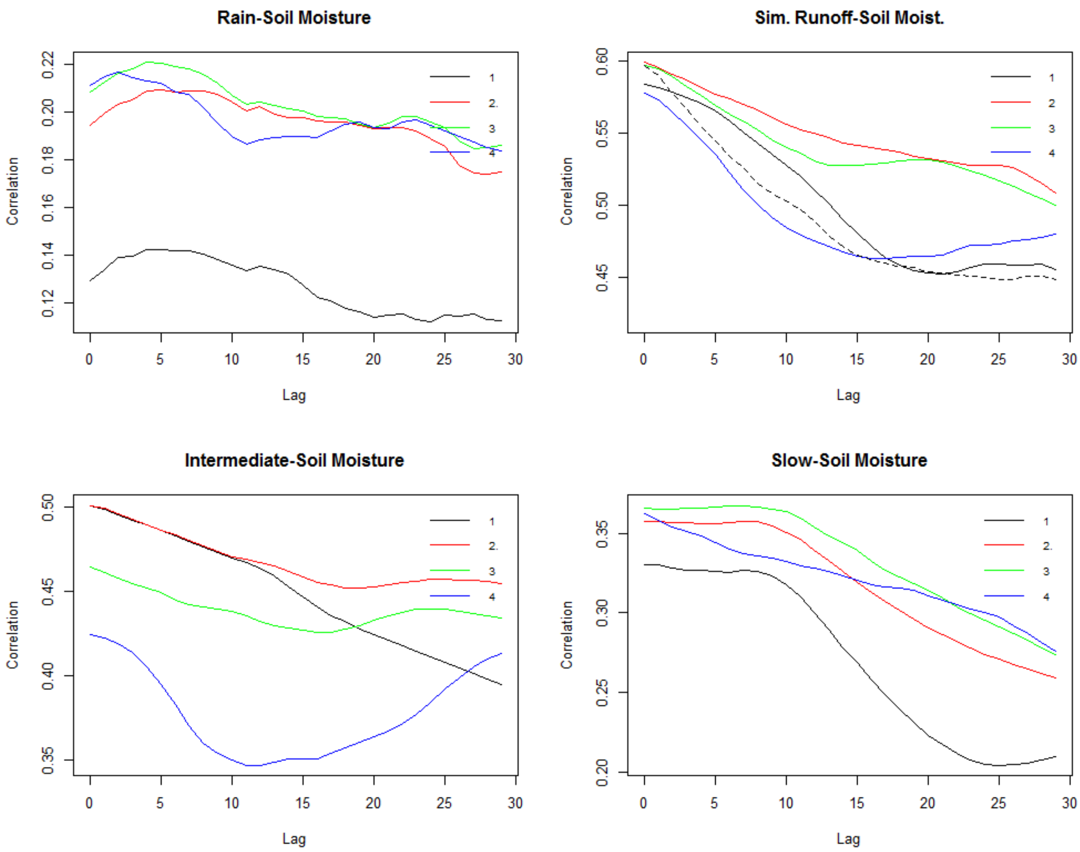

Figure 4.9: Four elevation zones semi-lumped model cross-correlation analysis for the soil moisture deficit time series. Zone 1 always refers to the lowest elevation zone. The dashed line is the cross-correlation between the aggregated soil moisture and observed runoff time series.

4.5 Event to event lag identification analysis

This section contains the event to event analysis in order to identify the lag of occurrence of the drought events. As explained before the lag time is defined as the distance of the centroid points of two consecutive events. Apart from the cross-correlation analysis this event to event analysis could be practical to validate the results from another point of view or identify significant trends that are not obvious in the aforementioned analysis.

Figure 4.10 illustrates the results for the lumped model for rain and soil moisture deficit time series. Each bar illustrates the amount of events that present lag time between the certain classes. The stacked bars represent each variable. The count of events is divided by the total number of events for each component. For example, in rain event to event analysis (Figure 4.9) 50% of the events of the simulated runoff deficit time series present lag time up to 5 days when compared to the rain deficit time series. Also, for the same case, almost 20% present lag time between 5 and 10 days. Adding bars of the same colour leads to 100%.

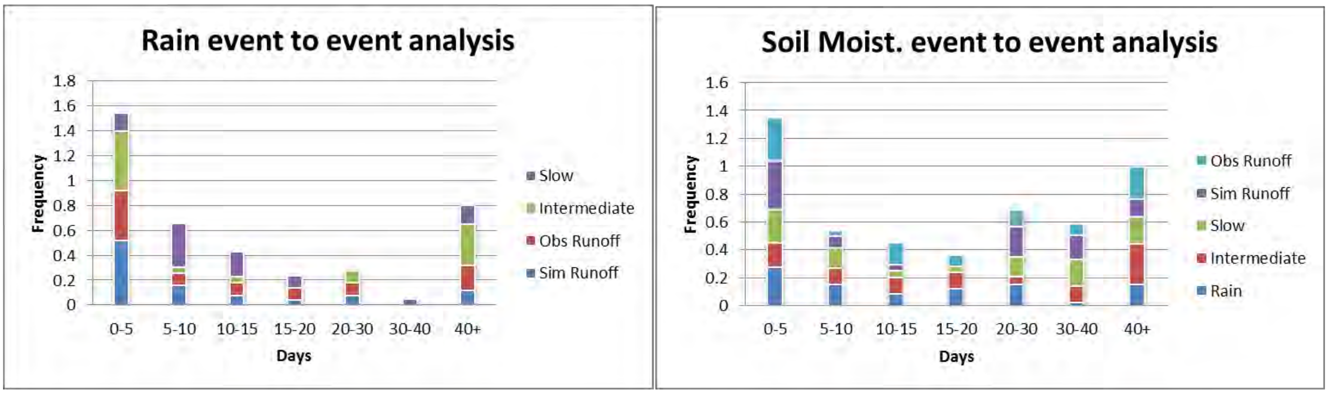

Figure 4.10: Lumped model event to event analysis results for rain (left) and soil moisture (right) deficit time series.

Figure 4.11 presents the results for the semi-lumped model with 2 elevation zones. The stacked bars represent the different components for each zone. Zone 1 (Z1) is the lowest elevation zone and zone 2 (Z2) the highest. Concerning the axis, they follow the same structure as mentioned for Figure 4.10.

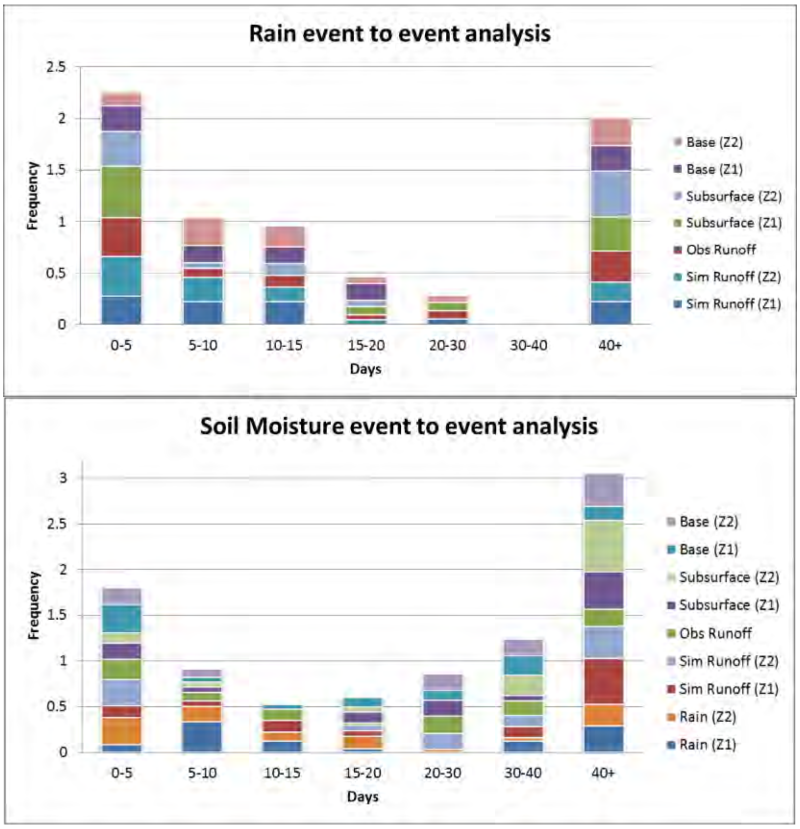

Figure 4.11: Semi-lumped model with 2 elevation zones, event to event analysis results for rain (top) and soil moisture (bottim) deficit time series. Z1 is the lowest elevation zone.

Figure 4.12 and 4.13 present the results for the semi-lumped model with 4 elevation zones for the rain and soil moisture event to event analysis, respectively.

The stacked bars present the elevation zones where zone 1 is the lowest and zone 4 the highest elevation zone; each graph correspond to a different component.

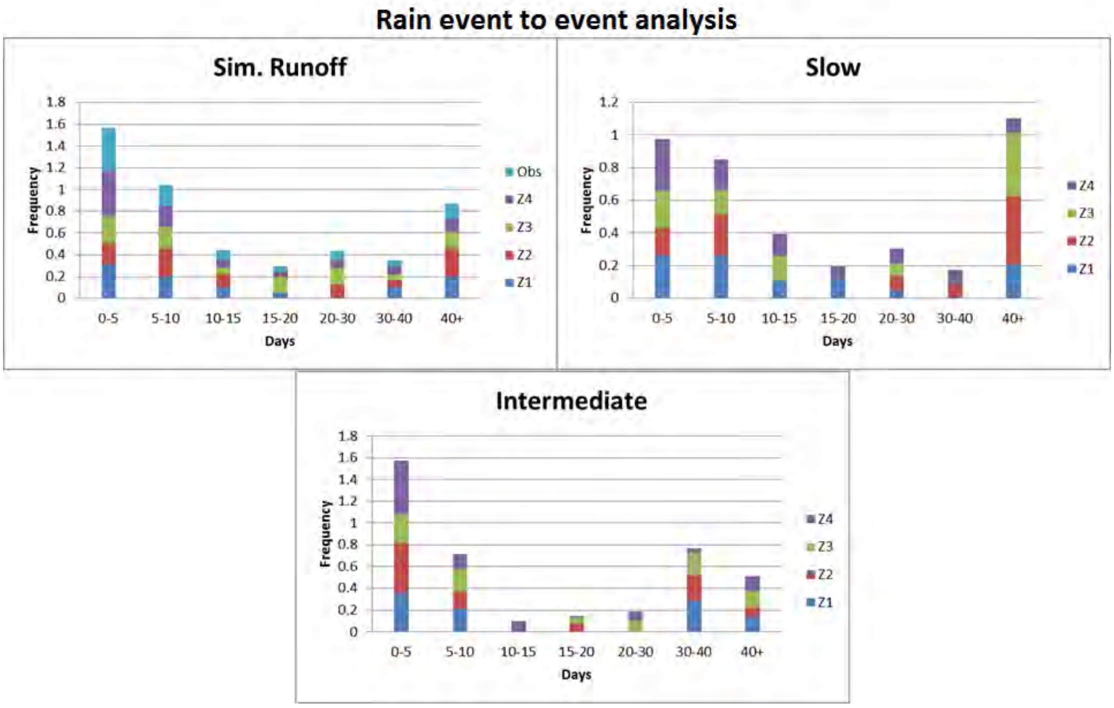

Figure 4.12: Semi-lumped model with 4 elevation zones, event to event analysis results for rain deficit time series. Z1 is the lowest and Z4 the highest elevation zone.

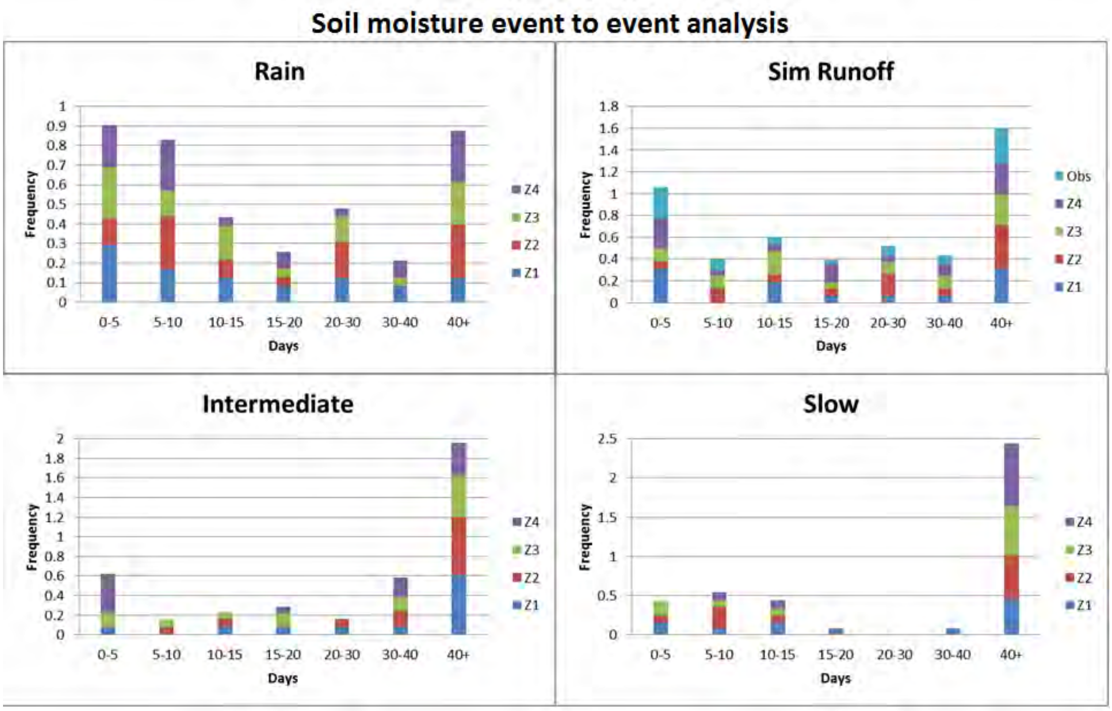

Figure 4.13: Semi-lumped model with 4 elevation zones, event to event analysis results for soil moisture deficit time series. Z1 is the lowest and Z4 the highest elevation zone.

4.6 Lag identification discussion

Two methods were used in order to identify the lag time of drought events (Chapter 3) i.e. a cross-correlation analysis comparing the rain and soil moisture deficit time series to the rest of the variables, concerning the timeframe of event occurrence and an event to event analysis that concern consecutive events. In general cross-correlation analysis is considered more reliable as it takes into consideration the whole time series. The event to event analysis is not giving significant trends because of the existence of events with high lag of occurrence, especially in the semi-lumped simulations. The reason we are not concerned about events with high occurring delay is because there is an uncertainty whether the events actually match in the two time series that are compared. The event to event analysis was very practical in order to check the cross-correlation analysis of the lumped model.

Concerning the lumped model the rain deficit time series cross-correlation (Figure 4.4) there is small or no lag present between the rain time series and the total simulated (2 days) and intermediate (no lag) runoff deficit time series. The slow runoff deficit time series present a characteristic delay of 13 days. These results are also evident in the event to event analysis. For the soil moisture deficit time series only the rain time series present a clear peak at 4 days (Figure 4.5). The total simulated runoff and the slow runoff follow the same pattern i.e. no lag peak present and fast decorrelation indicating the strong relationship between the occurrences of the drought events. The intermediate runoff presents no lag for the first 20 days and has a local maximum at 25 days that may refer to not consecutive events or, as the event to event analysis indicates, shows the existence of higher lags between the time series.

For the two zones semi-lumped model rain cross-correlation analysis higher elevation zones present smaller delays (Figure 4.6). As the total simulated and intermediate runoff of the highest zone follow similar patterns it can be deduced that the deficits of the total runoff time series is not affected by the slow runoff deficits. On the contrary on the low elevation zone the deficits seem to be driven by the slow runoff deficits, as there is a characteristic peak at 14 days that is also evident in the total simulated runoff graph. The same applies also in the four zones semi-lumped model rain cross-correlation analysis (Figure 4.7). As the delay of the deficits of zone 1, which is the lowest zone, is affected by the slow runoff component and the total simulated runoff of zone 4 follows the similar pattern with the intermediate component. Zone 2 and zone 3 seem to be affected by both. Specifically for zone 2 there are two characteristic peaks at the simulated runoff graph (at 3 and 16 days) that are present in the components also.

Regarding the rain and soil moisture cross-correlation analysis for the semi-lumped models (Figures 4.8 and 4.9), higher zones present earlier and steeper peaks than the lower zones. The simulated runoff deficits seem to be more affected by the slow component in the lower zones and more by the intermediate component in the higher zones.

Summarising, the rain cross-correlation analysis shows small delay between rain and total simulated as well as intermediate runoff deficits and higher delay in slow runoff component. The characteristic lag is presenting earlier in the higher elevation and is mostly related to the intermediate flow deficits. Slow runoff deficits affect lower elevation areas, fact that indicates that the flow is sustained by the slow runoff component.

A plausible hypothesis that could be made is that the different physical characteristics that are included in the elevation, such as the slope, affect the drought generating and propagation mechanisms. Higher elevation zones are usually steeper than the lower elevation zones, so there is a lower response time between rainfall and runoff. Considering that fact we can explain the earlier peak in higher zones as follows: when a rain deficit occurs the runoff water will leave the zone faster, due to steep slopes and there will be small delay until it is evident in the hydrological cycle.

Apart from the slope, the percolation rate is an important factor that could affect the procedure, even though there are no available data to validate this assumption. We can assume that in mountainous zones there are less impermeable layers than in lower areas. This fact can explain how the deficits that appear in the total runoff are connected to different hydrological component for each zone. For example combining that there are steep slopes and less permeability in higher zones it is sensible that the deficits are driven by the intermediate runoff (which is similar to the subsurface runoff) in the mountainous zones and by the slow runoff component in the low elevation areas.

The soil moisture cross-correlation analysis presents a characteristic delay between rain and soil moisture deficits that is smaller at the higher zones. As the analysis for the runoff components and soil moisture deficits does not contain clear patterns, what can be deduced is that the soil moisture deficits affect more the slow and total runoff deficits in the lower elevation while in higher elevation zones the intermediate zone is more affected. The hypotheses are made based on the same principles mentioned above.

4.7 Drought Events and Event Classification

This section contains information that concern the drought events characteristics i.e. the number of events per year the mean duration as well as the mean drought deficit and intensity of the events, as they were extracted from the application of a monthly threshold in the time series. Additionally, the events are investigated and categorised based on the theory mentioned in Chapter 3. As there is lack of snow in the study area only three categories were present i.e. classical rainfall deficit drought events, wet-to-dry-season drought events and composite events. The analysis was performed only for the exported results of the lumped model as it can generally be considered more reliable and it is also connected with the probabilistic analysis that will follow.

Table 4.2 illustrates the general drought characteristics as they were extracted for each variable using the selected threshold (Table 3.2) and Table 4.3 gives the percentages of all drought events for different variables that were attributed to a certain hydrological drought type.

Table 4.2: General drought characteristics using monthly threshold for different variables.

	Rain	Sim. Runoff	Obs. Runoff	Intermediate Runoff	Slow Runoff	Soil Moisture
Events per year	8.09	3.45	3.55	2.27	2.91	5.18
Mean duration (d)	25.31	83.41	83.34	141.80	99.03	40.82
Mean deficit (mm)	57.69	14.73	26.77	7.57	11.87	677.31
Mean intensity (mm/d)	2.87	0.13	0.24	0.13	0.05	9.39

Table 4.3: Hydrological drought types of all hydrological drought events per variable.

	Sim. Runoff	Obs. Runoff	Intermediate Runoff	Slow Runoff	Soil Moisture
Classical rainfall deficit droughts	55%	53%	60%	50%	42%
Wet to dry season droughts	32%	31%	8%	38%	37%
Composite droughts	13%	16%	32%	12%	21%

4.8 General drought characteristics discussion

The quantitative analysis that was performed for the lumped model (table 4.2) and concern the volume deficit and the duration of the events indicate the main pattern of the drought propagation. Rain time series present many events per year with shorter duration that are attenuated in the terrestrial zones in longer events. Even though the events are shorter they have greater severity and intensity from the other components. Storage capacity decreases the severity of the event and indicates that the ground slowly filters the drought propagation from zone to zone.

The intermediate runoff time series present the longer events. That is because it is highly affected by the dry periods between 1990-1992 and 1996-1997 returning drought events longer than a year. That is also evident in table 4.3 as it contains the highest percentage of composite drought events. Another thing that should be mentioned is the match between the observed and simulated time series.

Concerning the soil moisture time series it has very high mean deficit volume comparing to the rest of the variables. This indicates the effect of high temperature in the area. It is also present in table 4.3 as the soil moisture time series present the lower percentage of rainfall induced droughts.

Regarding the typology of the hydrological droughts (table 4.3) total and base runoff follow the same pattern. Intermediate runoff seems to be much more affected by the classical rainfall deficit droughts. Soil moisture time series, on the other hand, is mostly affected by the dry season occurrence. It should be noted that composite events in most of the cases are events with almost yearly length and that classical rainfall deficit drought events have in the majority longer length than wet-to-dry-season event that are mostly confined to summer season.

4.9 Probabilistic analysis

Figure 4.14 shows the estimation of the empirical return periods for the whole deficit time series. The deficit magnitude is divided by the average of each variable in order to be in comparable range. Table 4.2 indicate the mean deficit volume. Figure 4.15 illustrate the estimation of the empirical return levels for the duration of the events.

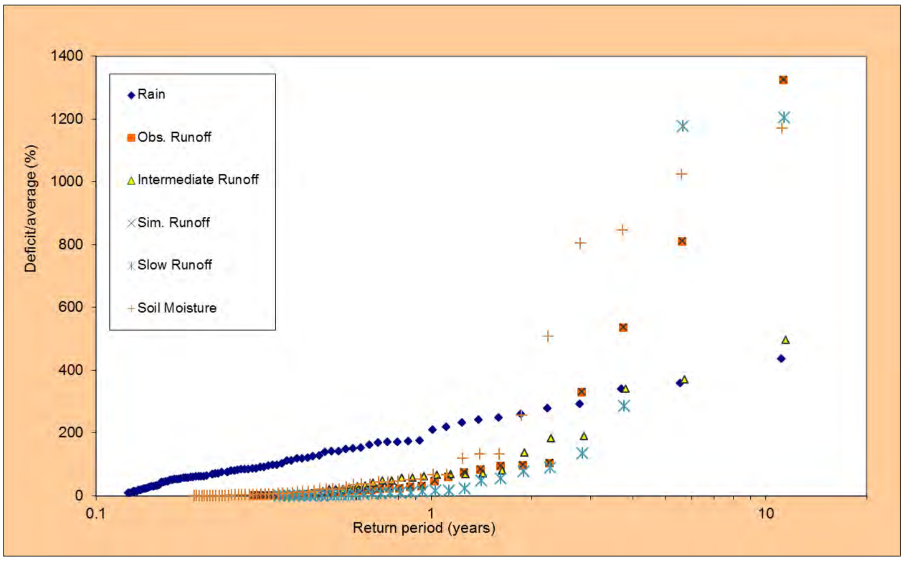

Figure 4.14: Empirical return levels for the whole deficit time series. The values are divided by the mean of each variable in so that the results are comparable. The abscissa is in logarithmic scale.

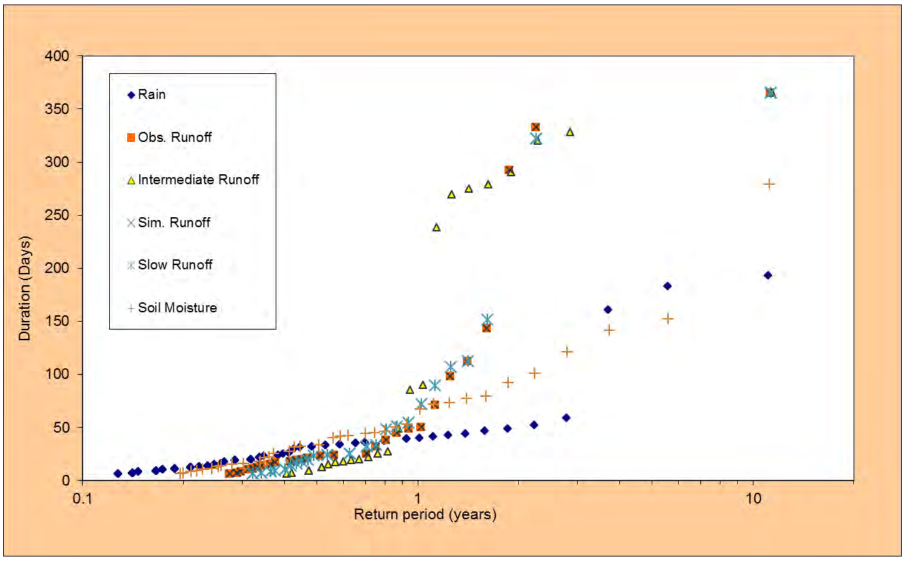

Figure 4.15: Empirical return levels estimation for the duration of the events as they were derived from the whole time series. The abscissa is in logarithmic scale.

The fitting of the distributions were performed for the lumped model in the volume deficit annual maxima time series as they were extracted after the application of monthly threshold. The optimum distributions were selected based on Kolmogorov–Smirnov test and the plots of the theoretical probability distribution function estimated return levels versus the empirical. Table 4.4 illustrates the selected distribution for each variable as well as the Kolmogorov–Smirnov test score and Figure 4.16 shows the actual fitting of the distribution. The parameters of the distributions are given in Table A2 in Appendix A. Equation 4.3 and 4.4 show the cumulative distribution function for the Pareto distribution and the probability density function for the Log Pearson III, where κ the shape, λ the scale and ψ the position parameters.

$$F(x) = 1 - \left[1 - \kappa\left(\frac{x}{\lambda} - \psi\right)\right]^{1/\kappa} \tag{4-3}$$

$$f(x) = \frac{1}{\lambda^{\kappa}\Gamma(\lambda)}(y-\psi)^{\kappa-1}e^{-(y-\psi)/\lambda}, \qquad y = \ln x \tag{4-4}$$

Table 4.4: Optimum distribution function for each variable and Kolmogorov–Smirnov test's evaluation.

		KS Test	
		a	D
Rain	Pareto (L-moments)	99.88%	0.09
Sim. Runoff	Pareto (L-moments)	87.80%	0.15
Obs. Runoff	Pareto (L-moments)	89.51%	0.14
Intermidiate Runoff	Pareto (L-moments)	97.37%	0.12
Slow Runoff	Pareto (L-moments)	99.92%	0.09
Soil Moisture	Log Pearson III	86.36%	0.15
	Pareto (L-moments)	83.02%	0.19

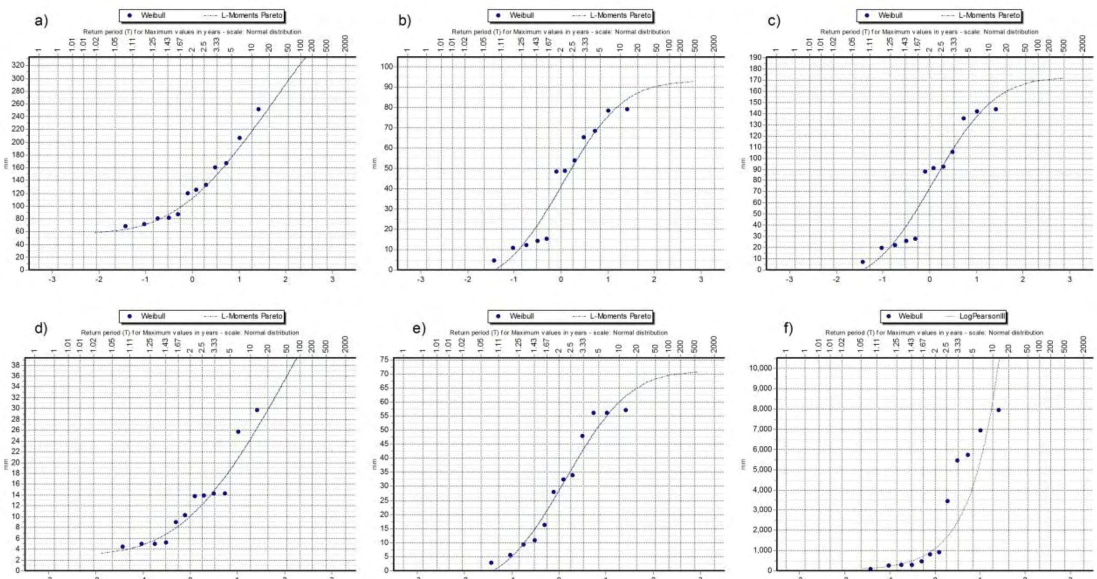

Figure 4.16: Theoretical distribution return levels versus empirical return levels where, a) rain, b) simulated runoff, c) observed runoff, d) intermediate runoff, e) slow runoff and f) soil moisture deficit annual maxima time series. It should be noted that the vertical axes are in millimeters as the sample correspond to volume deficit.

4.10 Probabilistic approach discussion

Taking into consideration that droughts in different components of the hydrological cycle affect different socio-economic factors it would be practical for water resources management applications to relate the metrological droughts to the drought that occur in each component from a probabilistic point of view. Fitting an accepted distribution gives the user the ability not only to predict future values and approximately estimate extreme events, but also can inter-connect the rain to the components of the flow.

The fitting of the distributions (Figure 4.16) which was evaluated through the Kolmogorov–Smirnov test (Table 4.4) is considered acceptable in most of the cases, even though there are discrepancies in the theoretical distribution fitting for the intermediate runoff and soil moisture annual maxima time series. In any case, even if the sample points are limited the fact that there is an optimum theoretical distribution (Pareto) accepted for almost all the cases supports the analysis. It should be noted that Pareto theoretical distribution was the second optimum (a=83.02%) but as the Log Pearson III had a better statistic score and visual fitting it was preferred. Also we need to clarify that as the time series were extracted from a threshold application they are partial duration series and the selection of Pareto is also supported [Madsen et al, 1997].

Concerning the empirical return periods estimated for the whole deficit series (Figure 4.14) the rain and intermediate runoff present a steady behavior and seem to converge to certain values (considering that it is a semi-logarithmic plot). On the other hand, the rest of the time series present extremely high values especially in the greater return periods. The duration empirical return periods (Figure 4.15) indicate that the runoff and its components are most prone to long drought events.

5 CONCLUSION

The study is investigating the propagation of droughts and the identification of them in the different components of the hydrological cycle. It stands as a methodology framework for relating meteorological droughts to hydrological drought and connect the drought events in the terrestrial parts with physical attributes such as the altitude. Based on the results of the study there is an evident relationship between the elevation of a catchment and the dominant drought prone zone. Also the study indicates how the seasonal pattern affects each part of the hydrological cycle in the hydrological event classification analysis.

The cross-correlation analysis has been very practical not only to understand the connection rain and soil moisture deficits with the corresponding deficits in the hydrologic component, but also to show the time of delay between two corresponding deficits in different variables. If, for example, the analysis was performed for a larger time series record length, in order to reduce any uncertainties, the characteristic lags that would be derived from the cross-correlation analysis would be characteristic for the basin also. Knowing that a deficit needs a certain amount of days to cascade from rain to runoff or to soil moisture could be useful information for operational purposes.

Moreover, the probabilistic analysis that was performed on the volume deficits provides information about the severity of the event. The analysis indicates that the deficit annual maxima series follow the Pareto distribution except from the soil moisture series. Performing the same analysis for the duration of the events and combining this information with a multivariate probability distribution (copula-based multivariate models) can give us a complete understanding of the catchment behaviour and can support any drought management objectives.

Concerning the tools used in this study there were several technical difficulties that need to be solved to complete the analysis. Luckily in R there are several tools concerning low flow analysis and in general is a user friendly and versatile environment, but as some of the tools are not unified or still missing key features, the user needs good data handling and imaginative skills, especially for larger data sets, in order to overcome these obstacles. Lastly, the certain case study was proved to be rather challenging, considering the actions taken in order to complete the low flow analysis, as the data set indicated that it is a strongly semi-arid area. Nevertheless, it is essential to study this type of catchments as they are the most exposed to drought hazards and can lead researchers in finding innovative and more efficient ways to analyse and deal with the phenomenon.

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APPENDIX A

Table A1: Estimated parameters of the TUWmdel.

	Lumped	Semi-Lumped (2 zones)	Semi-Lumped (4 zones)
SCF	1.1	1.2	1.2
DDF	1.6	4.1	1.9
Tr	2.9	1.8	2.6
Ts	0.2	-3	0.91
Tm	0.81	-0.56	-0.49
LP	0.61	0.19	0.46
FC	360	500	550
BETA	1.7	1.5	1.9
k0	1	0.51	1.1
k1	5.9	3.3	1.7
k2	76	31	35
lsuz	24	19	27
cperc	0.91	1.5	0.95
bmax	0.18	2.3	1.1
cr	4.3	16	4.9
SSM0	50	50	50
SWE0	0	0	0
SZ0	2.5	2.5	2.5
SLZ0	2.5	2.5	2.5

Table A2: Estimated parameters of the fitted distribution with the use of Hydrognomon.

		kappa	lamda	psi
Rain	Pareto (L-moments)	0.18	85.43	0.66
Sim. Runoff	Pareto (L-moments)	0.95	95.72	-0.08
Obs. Runoff	Pareto (L-moments)	0.90	166.83	-0.08
Intermidiate Runoff	Pareto (L-moments)	0.13	10.76	0.27
Slow Runoff	Pareto (L-moments)	0.84	64.27	-0.08
Soil Moisture	Log Pearson III	386.59	12.36	-24.28

APPENDIX B

Snow routine

The snow routine represents snow accumulation and melt by a simple degree-day concept. Mean daily precipitation P in an elevation zone is partitioned into rain P_R and snow P_S based on the mean daily air temperature.

T_A:

$$\begin{aligned} P_R &= P & &\text{if } T_A \geq T_R \\ P_R &= P\frac{T_A - T_S}{T_R - T_S} & &\text{if } T_S < T_A < T_R \\ P_R &= 0 & &\text{if } T_A < T_S \\ P_S &= P - P_R \end{aligned} \tag{B-1}$$

where T_S and T_R are the lower and upper threshold temperatures respectively. Melt starts at air temperatures above a threshold T_M:

$$M = (T_A - T_M)\mathrm{DDF} \qquad \text{if } T_A > T_M \text{ and SWE} > 0 \tag{B-2}$$

where, M is the amount of melt water per time step, DDF is the degree-day factor and SWE is the snow water equivalent. The catch deficit of the precipitation gauges during snowfall is corrected by a snow correction factor SCF. Changes in the snow water equivalent from days *i* -1 to *i* are accounted by Equation (B-3) that follows, where Δt is the time step of 1 day.

$$\mathrm{SWE}_i = \mathrm{SWE}_{i-1} + (\mathrm{SCF}P_\mathrm{S} - M)\Delta t \quad \text{(B-3)}$$

Soil moisture routine

The soil moisture routine represents runoff generationand changes in the soil moisture state of the catchment

$$S_{\mathrm{SM},i} = S_{\mathrm{SM},1-i} + P_\mathrm{R} + M - E_\mathrm{A} \quad \text{(B-4)}$$

Where, S_{SM} is the soil moisture of a top soil layer controlling runoff generation and actual evaporation E_A. The contribution ΔSUZ of rain and snowmelt to runoff is calculated by an explicit scheme as a function of the soil moisture of the top layer SSM using a non-linear relationship with two free parameters, FC and β:

$$\Delta S_\mathrm{UZ} = \left(\frac{S_\mathrm{SM}}{\mathrm{FC}}\right)^\beta (P_\mathrm{R} + M) \quad \text{(B-5)}$$

FC is the maximum soil moisture storage. The parameter β controls the characteristics of runoff generation and is a non-linearity parameter. If the top soil layer is saturated, i.e. SSM D FC, then all rainfall and snowmelt contributes to runoff. The actual evaporation EA is calculated from potential evaporation EP by a piecewise linear function of the soil moisture of the top layer:

$$\begin{aligned} E_\mathrm{A} &= E_\mathrm{P}\frac{S_\mathrm{SM}}{\mathrm{LP}} & \text{if } S_\mathrm{SM} < \mathrm{LP} \\ E_\mathrm{A} &= E_\mathrm{P} & \text{if } S_\mathrm{SM} \geq \mathrm{LP} \end{aligned} \quad \text{(B-6)}$$

where, LP is a parameter termed the limit for potential evapotransipiration E_P.

Response and transfer function

The storage states of the upper and lower zones are SUZ and SLZ respectively. LSUZ enters the upper zone reservoir and leaves this reservoir through three paths: outflow from the reservoir with a fast storage coefficient of K1, percolation to the lower zone with a constant percolation rate C_P, and, if a threshold LSUZ of the storage state is exceeded, through an additional outlet with a storage coefficient of K0. Water leaves the lower zone with a slow storage coefficient of K2. The outflow from both reservoirs Q_G is then routed by a triangular transfer function, which represents the runoff routing in the streams:

$$
\begin{aligned}
&B_Q = B_{\mathrm{MAX}} - C_{\mathrm{R}} Q_{\mathrm{G}} && \text{if } (B_{\mathrm{MAX}} - C_{\mathrm{R}} Q_{\mathrm{G}}) \geq 1 \\
&B_Q = 1 && \text{otherwise}
\end{aligned} \qquad \text{(B-7)}
$$

where, B_Q is the base of the transfer (triangular) function, B_{MAX} is the maximum base at low flows and C_R is a free scaling parameter.