Reply to the Handling Editor and Reviewers

We thank the Editor for handling the review process, and the three anonymous Reviewers for evaluating our work. We have implemented all applicable recommendations that improve the quality of the original manuscript. Some preliminary replies to the comments received were posted already during the public discussion step of the journal, and more targeted point-by-point responses are given below. To avoid confusion, all line numbers refer to the revised version of the manuscript (attached to the response letter), where all changes are properly tracked. Finally, please note a native English speaker, with expertise in environmental sciences, has fine-tuned all parts of the revised paper and this reply.

Reply to the Handling Editor

Dear Authors,
after receiving three reviews, and by reading your answers to the comments and suggestions made by the reviewers, I am convinced that the manuscript can be enhanced and made more readable with a clear research question(s) and final message what your research results bring to the scientific community, at least in the Mediterranean area.
Please, prepare a revised manuscript at your earliest convenience by incorporating into it your answers from the discussion phase.
The revised manuscript will be reviewed again by at least one reviewer and myself.
Sincerely Yours,
MatjažMikoš
Handling Editor

REPLY: We thank the Editor for handling the review process of our original submission and for providing useful recommendations on how to improve the manuscript. In the following, we provide our final replies to the three reviewers who evaluated our original paper during the public discussion step of the journal. We tried to thoroughly reformulate the last part of the Introduction (lines 64-100) to clarify the research question, the goal of our study, the novelty proposed by this study and the conclusions. We followed almost all comments and suggestions received from the three reviewers, especially by improving the description of the methods and clarity in reporting results and comments.

General comments from the authors on reviewers' reports

Three reviewers evaluated our original manuscript, making interesting comments but also raising some concerns. A few concerns refer to general matters, whereas the rest are mostly linked to their personal views on the topic of our study. While there is a consensus on the quality with which we presented our investigation, the opinions were somewhat more critical on the scientific significance and how we discussed our results.
In the light of the comments and recommendations received, we have revised the introduction and better focused (we do hope) the main research question that guided our present study. We have put considerable effort into the revised manuscript to clarify those parts that might give rise to strong criticisms. In the event of disagreement with some reviewer's criticism, we shall give adequate reasons for our position.
We also changed the title. The new one is: "Assessing the impact of seasonal rainfall anomalies on catchment-scale water balance components".

Reply to Referee #1

COMMENT 1.1. General comments: In the submitted paper, authors investigate the impact of the rainfall seasonality anomalies on the catchment water balance components. For this purpose, a catchment in the southern Italy is selected and SWAT model is applied in order to carry out the investigation. Two different approaches are used in order to define rainfall scenarios. First approach is based on the standardized precipitation index and second one is based on the duration of the wet season as proposed by Feng et al. (2013). The topic is potentially interesting for the society and HESS readers.

REPLY-1.1. We thank this reviewer for her/his positive comments and appreciation of the potential interest in our work.

However, two main shortcomings of the paper from my perspective that should be improved are:

COMMENT 1.2. Firstly, the main focus of the paper is to investigate what is the impact of different rainfall scenarios on the water yield, actual evapotranspiration and groundwater recharge. Thus, for different scenarios changes in these variables are analyzed with respect to reference case. Model calibration is just briefly described and reference to more detailed description is given (Nesta et al., 2017). It seems that model was calibrated using monthly data (?). However, P6, L124 states that daily time step of the SWAT model was used. I think that model should also be calibrated using daily data if authors want to use this time step. Otherwise, I would suggest to aggregate daily rainfall data into monthly and re-run the model with monthly time step (if this is possible or perhaps use a different model). An alternative is, to calibrate the model using daily data if there is a discharge gauging station available near the catchment outlet.
REPLY-1.2. Nasta et al. (2017 STotEnv) calibrated nine model parameters by comparing measured and simulated monthly water yields recorded at the dam. Numerical simulations were run at the daily time step (the only time step allowed in SWAT). In this study, we followed the same criterion: we ran numerical simulations at the daily time step (rainfall was randomly generated at the daily time step) and aggregated the output fluxes at a monthly time resolution. We are aware that calibrating at the monthly time-scale might lead to a potential misfit between measured and simulated values at a daily time-scale (e.g. Adla et al., 2019, Water). However, our analysis is based on the monthly aggregation of fluxes and we analyzed seasonal patterns of monthly aggregates. In the light of the above comment, we added a new part at lines 182-188 to clarify this important point and why this misfit should not be viewed as relevant to our analysis. The reference to the paper by Adla et al. (2019) is also added.

Adla, S., S. Tripathi, M. Disse, 2019. Can we calibrate a daily time-step hydrological model using monthly time-step discharge data? Water 11, 1750; doi:10.3390/w11091750.

COMMENT 1.3. Secondly, when using different scenarios, authors only modified rainfall characteristics, what about air temperature? It is true that in some cases the dependence between these two variables can be low or even none existing. However, is some other cases, some dependence could exist. For example, higher average annual temperature could lead to lower annual rainfall and vice-versa. Or higher daily temperature in summer could cause higher rainfall amounts due to more extreme thunderstorm. Did authors check the relationship for this specific catchment? Moreover, I think that air temperature variability should be included in this kind of investigations. Even if there is no clear relationship with rainfall.
REPLY-1.3. We fully agree with this comment, which in our opinion is timely. Indeed, the feedback of temperature on precipitation is a widely recognized cause for the increasing frequency of storms and heavy rainfall events under climate change. Unfortunately, we do not have easy access to a database of long time series of observed temperatures to reliably evaluate this linkage in our case study. However, one should note that this kind of information cannot be restricted only to the surrounding air temperatures, but should include the change in the sea surface temperature and air moisture to correctly frame the analysis. This is certainly an issue that deserves an in-depth investigation, but it goes beyond the scope of our study. We focused only on the long-term (almost one century) daily time series of rainfall, yielding interesting outcomes about the sensitivity of catchment hydrological response to seasonal rainfall patterns alone. Moreover, for the same reason (lack of comprehensive spatial and temporal sets of temperature data), we were unable to capture any significant (increasing) trend and assumed the temperature is stationary in time and so is evapotranspiration (although, of course we reproduce the seasonal cycle). Our analysis addressed only the impact exerted by rainfall seasonality on the major water balance components. The availability of adequate datasets should highlight whether the observed increases in air temperatures impact the daily precipitations, or mostly only the sub-daily and sub-hourly rainfall values.
In any case, we took care of temperature variability (and temporal variability of all weather data) because daily potential evapotranspiration data were calculated by using random values of weather data drawn

from their normal distribution in each month of the year. We reformulated this part by clarifying sentences (lines 167-172)

Specific comments:
I would suggest to add a figure showing the location of the catchment with stations used.
REPLY-1.4. We added the new Fig. 1 and have accordingly changed the figure numbering throughout the revised manuscript.

P6, L130: Please better explain what is meant by the term boundary forcings.
REPLY-1.5. With the term "boundary forcings", we mean the (input) water fluxes (rainfall and potential evapotranspiration) set as upper boundary conditions to the flow domain.
To avoid misunderstanding we rephrased all occurrences of "boundary forcings" with "rainfall and potential evapotranspiration forcings". We modified also y-axis title in Fig. 10 as well.

P7, L142-144: Why did you used only 3 years for simulation and why 2-years warm-up period? How does this selection impact on the results? Moreover, does initial state of the catchment also has impact on the results (i.e. using different initial values of model variables)?
REPLY-1.6. We decided to run three years in each scenario and neglect the model simulations of the first two years to annihilate the impact of initial soil moisture values set in the soil domain. We point out that the soil moisture content at the initial day of year 1 is set at the value of "field capacity" (which can be already considered a realistic situation in winter under Mediterranean climate). Moreover, we have considered the third year of model simulation. We repeat this exercise 10,000 times so as to frame the output fluxes within a probabilistic framework. We added this clarification in the text (see lines 189-196)

P7, L146-149: The data from other station will be used for analyses at monthly time scale but the model will run with daily time step and daily reference evapotranspiration will be calculated? Perhaps you could rephrase this sentence.
REPLY-1.7. We agree and we reformulate this (unclear) sentence. We have the daily weather values and we use the descriptive statistics of daily values in each month of the year to generate new random daily values of evapotranspiration in each month. See also reply1.3. Sentences in lines 196-200 were rephrased.

P7, L149: Here reference evapotranspiration is mentioned but in next sections, you only mention potential and actual evapotranspiration. Why was reference evapotranspiration used?
REPLY-1.8. SWAT uses weather data to estimate potential evapotranspiration (ET_p). We replaced the word "reference" with the word "potential" at line 201. Thanks for pointing it out.

P9, section 4.3: If I understand correctly exponential distribution was selected only based on the graphical comparison shown in Figure 2 and Figure 3? If this is the case, I would suggest to additionally apply a suitable statistical test.
REPLY-1.9. The stochastic Poisson point process of daily rainfall occurrences was assumed to represent daily rainfall evolution for its easy reproducibility (Lines 252-254). In a preliminary analysis, we tested it and compared it with the best parent distribution, namely the Generalized Pareto Distribution. In this case, we observed a fair agreement between the two models for representing the daily rainfall evolution recorded at the Gioi Cilento weather station, and concluded that the simple-to-use exponential model is suitable (Lines 267-269).
The stochastic Poisson point process is widely used for its simplicity and parsimony as pointed out by Reviewer#2 (we list below the three references reported in Reply 2.4 to Reviewer #2).

Rodríguez-Iturbe, I., B. Febres de Power, J.B. Valdés. 1987. Rectangular pulses point process models for rainfall: Analysis of empirical data. Journal of Geophysical Research, https://doi.org/10.1029/JD092iD08p09645
Veneziano, D., V. Iacobellis. 2002. Multiscaling pulse representation of temporal rainfall. Water Resources Research, 38, 1138, 10.1029/2001WR000522
Eagleson, P. S. 1972. Dynamics of flood frequency. Water Resour. Res., 8, 878–898.

P10, L230-231: I do not understand this sentence, if you split the data, how can you then have a drying trend? Only for the second 45 years?

REPLY-1.10. The frequency distribution of SPI-6 values in the first 45 years is wetter than the one pertaining to the last (more recent) 45 years. This is now clarified at Lines 306-312.

P13, L285 and L294: A statistical test is mentioned here but no information about null and alternative hypothesis is given. Moreover, authors should rephrase these sentences. In statistical hypothesis testing the null hypothesis can be either rejected in favor of the alternative hypothesis or cannot be rejected (with the chosen significance level). Moreover, all the methods used should probably be mentioned and described in the methodology section (and not results and discussion).

REPLY-1.11. The Mann-Kendal test has become a standard test to search for a possible trend in a time series and is widely applied in the literature. Therefore, after a discussion among the co-authors, we decided not to describe the Mann-Kendal test in detail and just mentioned the reference.

Sections 5.3 and 5.4 and conclusions: The main results of the paper are somehow expected: dry scenario leads to less runoff, groundwater recharge and also less actual evapotranspiration (compared to reference scenario). On the other hand, wet scenario leads to more runoff, groundwater recharge and actual evapotranspiration (compared to reference scenario). Moreover, different rainfall simulation methods yield different results. The actual relationship among variables mostly depends on the rainfall characteristics, especially if variability in air temperature is not considered. Can the authors perhaps somehow enhance the take home message of this paper?

REPLY-1.12. The target of our study is to evaluate the sensitivity of some water balance components to seasonal rainfall anomalies (potential temperature effects are not considered here, partly because of the lack of suitable datasets). We thoroughly reformulated the conclusion section by highlighting the take-home message of this paper. We recalled the main research question that we posed in the Introduction: "What is the impact of seasonal rainfall anomalies on annual-average (or seasonal-average) water supply in UARC?"

We briefly present the following steps to answer the aforementioned question: 1) we needed to build robust scenarios based on well-posed hydrological model (SWAT) by presenting results within a probabilistic framework; 2) to do that, we need to analyze the long-term historical rainfall time series and identify rainfall seasons; 3) evaluate the best statistical distribution of rainfall daily values (Poisson model) in each season; 4) propose two approaches to detect seasonal rainfall anomalies and stress pros and cons.

Moreover, the assumption of the steady-state condition inherent in the Budyko approach is questioned. The stationarity/non-stationarity dilemma in hydrological processes is still a matter of an open debate in the scientific community (Milly et al., 2008; Montanari and Koutsoyiannis, 2014).

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management?Science,319:573–574.

Montanari, A., and D. Koutsoyiannis. 2014. Modeling and mitigating natural hazards: Stationarity is immortal!Water Resour. Res.,50:9748–9756.

Reply to Referee #2

The paper deals with the assessment of water balance components (i.e. water yield, evapotranspiration, groundwater recharge, etc.) and relative deficit in case of climatic anomalies related to seasonality in a Mediterranean basin. This is done by parameterizing a rainfall generator model according to two different schematic representation of seasonality (called "static" and "dynamic"), and using synthetic rainfall series as input to the SWAT hydrological model. While shifts and changes in seasonal patterns have been addressed by many researchers as key factors in analyzing the hydrological impact of climatic fluctuations, the consequent issue of how these phenomena may impact the regulation of artificial reservoirs, designed for annual or multiyear storage purpose, deserves attention.

GENERAL REPLY: We thank this reviewer for her/his comments and suggestions.

The paper is in general well sounded and relevant although it could be improved in my opinion, accounting for the following suggestions. The paper is compound by two main issues:
2.1. The first one is referred to the analysis of the climatic forcing and the parameterization of the rainfall model; the second one is related to the use of SWAT model to obtain different components of water balance. A stronger emphasis is given to the first one, which is also performed by comparing different methods, while the second one is much less discussed. Also, the overall paper goal could be better assessed and the methodology more detailed in the introduction. To make an example, the sentence "The goal of the study is to characterize the rainfall seasonality and its anomalies by using two approaches." (line 81) is in my opinion somehow misleading with respect to the overall paper objectives and developments.
REPLY-2.1. We agree with this concern that was also raised by Ref.#3 (see our Reply 3.1). Therefore, we have completely reformulated the last part of the Introduction (Lines 69-117) and overhauled the conclusions (Lines 523-583) to make the paper more effective and clarify our goals and take-home messages (see also Reply 1.12 to Ref.#1).

2.2. Dealing with issue #1, i.e. seasonality assessment, in the introduction the PCI and SI methods are indicated as most popular approaches. Nevertheless, the authors do not use them but rather prefer an SPI based analysis and the procedure proposed by Feng et al (2013). A better acknowledgement could be provided about the reasons of such choices, and the comparisons between the performances of different methods.
REPLY-2.2. Basically, our introduction lists some seasonality indexes, which indicate qualitatively the degree of rainfall seasonality in a given precipitation time-series. To assess rainfall seasonality quantitatively, among the various existing techniques, the SPI index and the Feng et al. approach appeared to be sound techniques to classify wet and dry months as well as to retrieve precious information on the statistical distribution of daily rainfall values.
We added the following new sentence in lines 81-96: "Nonetheless, while PCI and SI are useful indexes to classify rainfall seasonality and the degree of concentration of rainfall within the year, their implementation in a Monte Carlo framework is not straightforward. Therefore, we opted to characterize rainfall seasonality and its anomalies by using the two approaches described as follows. A first approach, which is hereafter referred to as the static approach, is based on the analysis of the standardized precipitation index (SPI) to define the duration of a wet season (4 months), a dry season (4 months) and a transition season (2 months from dry to wet phase plus 2 months from wet to dry phase) in UARC. In this approach, the drought anomaly is rigidly built with the artifact of extending the duration of the dry season to eight months by removing the transition season. The same criterion applies to a prolonged duration of the rainy season. The second approach, instead, exploits the seasonality characterization proposed by Feng et al. (2013) and can be viewed as a dynamic approach since the duration of the rainy season is time-variant (inter-annual variability) and can be stochastically generated with random duration values drawn from their statistical distribution. This second approach investigates what happens to the water budget if the duration of the rainy season becomes shorter-than-normal (i.e. rainfall scarcity) or longer-than-normal (i.e. rainfall excess). As far as we are aware, there is still a lack of knowledge about the effects of possible changes in rainfall seasonality on the water balance of a catchment subject to a Mediterranean climate, and the analyses presented in this paper aim primarily to contribute to fill this gap.".

2.3. At line 184 the authors state that they "assumed that the duration of the wet season follows a normal distribution...". While I do not doubt that such hypothesis may be a feasible one, I would expect some kind of validation or testing of it through observed data.
REPLY-2.3. We strongly agree with this comment. Actually, we applied the Lilliefors test for normality in Section 5.2 (lines 382-391), and also anticipated this result in section 4.2 (lines 238-243).

2.4. The stochastic Poisson point process with exponential distribution of pulses that is finally used for rainfall generations, I believe could be referenced to classical papers like Rodriguez-Iturbe, I. et al (Journal of Geophysical Research, 1987) and /or Eagleson (WRR, 1972), may be also of interest a more recent application by Veneziano and Iacobellis (WRR, 2002) on Italian datasets, among many others. The use of seasonal parameterization on a stochastic rainfall generator is also a matter of interest.

REPLY-2.4. We agree and added the three mentioned citations accordingly (lines 254-255).

Rodríguez-Iturbe, I., B. Febres de Power, J.B. Valdés. 1987. Rectangular pulses point process models for rainfall: Analysis of empirical data. Journal of Geophysical Research, https://doi.org/10.1029/JD092iD08p09645.
Veneziano, D., V. Iacobellis. 2002. Multiscaling pulse representation of temporal rainfall. Water Resources Research, 38, 1138, 10.1029/2001WR000522
Eagleson, P.S. 1972. Dynamics of flood frequency. Water Resour. Res.,8, 878–898.

2.5. I believe that also conclusions should be reinforced. First by better depicting which practical use the methodology could be exploited for and, second, by deepening the discussion about the characterization of rainfall seasonality and its anomalies, according to different approaches, which was mentioned as a goal of the study.
REPLY-2.5. We strongly agree with this comment, which was also stated by Ref.#1 (Reply1.12). We therefore report the same reply below.
The target of our study is to evaluate the sensitivity of water balance components to seasonal rainfall anomalies (potential temperature effects are not considered here, partly because of the lack of suitable datasets). We thoroughly reformulated the Conclusions Section by highlighting the take-home message of this paper. We recalled the main research question that we posed in the Introduction: "What is the impact of seasonal rainfall anomalies on annual-average (or seasonal-average) water supply in UARC?"
We briefly present the following steps to answer the aforementioned question: 1) we needed to build robust scenarios based on well-posed hydrological model (SWAT) by presenting results within a probabilistic framework; 2) to do that, we need to analyze the long term historical rainfall time series and identify rainfall seasons; 3) evaluate the best statistical distribution of rainfall daily values (Poisson model) in each season; 4) propose two approaches to detect rainfall seasonality anomalies and stress pros and cons.
Moreover, the assumption of the steady-state condition inherent in the Budyko approach is questioned. The stationarity/non-stationarity dilemma in hydrological processes is still a matter of an open debate in the scientific community (Milly et al., 2008; Montanari and Koutsoyiannis, 2014).

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? Science, 319:573–574.
Montanari, A., and D. Koutsoyiannis. 2014. Modeling and mitigating natural hazards: Stationarity is immortal! Water Resour. Res., 50:9748–9756.

Reply to Referee #3

The main research question of this study, as presented by the authors in Line 64, is "What is the impact of rainfall seasonality anomalies on annual-average (or seasonal-average) water supply, and what happens if the Alento River catchment (ARC) will experience several consecutive years of lower-than-expected rainfall events?" The authors use SWAT (Soil Water Assessment Tool) to assess the changes in the different catchment water fluxes in response to changes in rainfall seasonality, using ARC as a study site. The changes in rainfall seasonality is simulated through two different approaches: (i) a "static" approach based on the SPI (Standard Precipitaiton Index) and (ii) a "dynamic" approach by decomposing seasonality into a magnitude, timing, and duration components following Feng et al. 2013. While simulating the changes in rainfall seasonality via a Monte-Carlo approach, the length of the seasons are set across multiple years but varied across the 3 case scenarios ("reference," "dry," and "wet") for the "static" approach, whereas for the "dynamic" approach, the duration of the wet season in each year is randomly drawn from a normal distribution (line 220 – 222).
GENERAL REPLY: We thank this reviewer for her/his comments and suggestions.

To me, the set of main questions is at once too broad ("the effect of rainfall seasonality on the annual catchment water yield") and too specific (effects on one catchment, ARC). The presentation is overall loose and acutely needs focusing. By this I mean that it's not clear to me what conclusions to be drawn from this study other than "by changing rainfall seasonality under scenario X, we simulated a reduction in water yield at this Mediterranean catchment by Y amount," which does not give much scientific insights into how this particular Mediterranean catchment might function (in response to the second part of the main question), nor how the results may be able to be generalized to other Mediterranean catchments around the world (in response to the first part of the main question). Perhaps this is just an issue of having to refine the main question a little more. At one point the authors also state “the goal of this study is to characterize the rainfall seasonality and its anomalies by using two approaches (Line 84)” – to what end? Not only do I find this goal to be a little aimless, but it’s also not clear to me how this would help advance the overall research question stated earlier. I understand that this relates to the methodology through which the main questions were interrogated, but why two different approaches? And what did the authors learn from adopting the two different approaches?

REPLY-3.1. Almost all of the papers we read in the literature refer to a general problem or concern that seasonality is investigated in one specific area where a good amount of quality data is available to elucidate somehow the question at hand. Moreover, especially in recent years, it is desirable to compare outcomes from different sites, an exercise made difficult since only in very few cases are the experimental sites instrumented in similar ways. One eventually tries to get the most from one’s own site and hopes that these outcomes can be exported to similar sites.

While we do agree with this reviewer that the main research question we pose in this paper should be refined somehow and better worded, we are confident that the “static” and “dynamic” implementations discussed in the manuscript will contribute giving answer to some timely but still unexplored (at our best knowledge) issues, that are relevant to the Mediterranean rainfall seasonality. Specifically, the “static” approach (based on SPI) addresses the issue “*What happens to the water budget if the transition season becomes dry or wet?*”; while the “dynamic” approach, allowing the wet season to vary from year to year and thus accounting for inter-annual variability, aims to answer the question “*What happens to the water budget if the spread of the wet season becomes smaller-than-average (short duration of the wet season, meaning drought) or larger-than-average (long duration of the wet season)?*”

By exploiting a long-term rainfall time series, an element of novelty of this manuscript is to assess the impact of wet season duration on the water budget in a river catchment with the UARC features. However, a longer-than-average duration of the wet season does not “always” imply a wetter-than-average mean annual rainfall. We do have to take into account also rainfall magnitude of the wet season. The strategy is to analyze rainfall data and properly characterize the duration and magnitude of rainfall seasons through a Monte-Carlo approach since we want to obtain water budget results within a probabilistic framework.

In light of the above comment and also the other two reviewers’ comments, we completely changed the last part of the Introduction. Please see lines 69-117 and by following similar concerns raised by Reviewer#1 (Reply 1.12) and Reviewer#2 (Reply 2.5) overhauled the Conclusions (Lines 523-583)

The authors claim that the questions of how the catchment water balance plays out in Mediterranean question remains largely unaddressed (“As far as we are aware, there is still a lack of knowledge about the effects of possible changes in rainfall seasonality on the water balance of a catchment subject to a Mediterranean climate, and the analyses presented in this paper aims primarily at contributing to fill this gap.” (Lines 84 – 86) I find this statement to be surprising and again, vague and unrefined, since there is already a large body of work that already attempts to address this question in one fashion or another, via theoretical and empirical approaches, that remains uncited:

– Potter et al. 2005 “Effects of rainfall seasonality and soil moisture capacity on mean annual water balance for Australian catchments” WRR.
– Hickel and Zhang 2006. “Estimating the impact of rainfall seasonality on mean annual water balance using a top-down approach” JoH.
– Viola et al. 2008 “Transient soil-moisture dynamics and climate change in Mediterranean ecosystems” WRR.
– Gentine et al. 2012 “Interdependence of climate, soil, and vegetation as constrained by the Budyko curve.” GRL
– Andersen et al. 2012 “Assessing regional evapotranspiration and water balance across a Mediterranean montane climate gradient.” AFM
– Williams et al. 2012 “Climate and vegetation controls on the surface water balance: Synthesis of evapotranspiration measured across a global network of flux towers” WRR

- Feng et al. 2015 “Stochastic soil water balance under seasonal climates” PRSA
- Viola et al. 2019 “Impacts of hydrological changes on annual runoff distribution in seasonally dry basins” WRM

The authors do not make an attempt to contextualize the results of their work against a larger set of studies on water balance in seasonal and Mediterranean climates, and I find this disappointing. My goal in listing these references is not to encourage the authors to simply cite them, but also to use them (amongst others that I have certainly missed) as a starting point to actually pinpoint where the existing knowledge gaps are, and articulate clearly how, using the current approach, they are able to fill them. For example, the fact that we need to account for climate seasonality and non-stationarity when considering annual water balances, to me, does NOT constitute a knowledge gap – this has been the conclusion of many previous papers.
REPLY-3.2. Actually, in the original manuscript we did cite Potter et al. (2005) (see line 73) and Williams et al. (2012) (see line 393). Other than that, we have cited the papers related to the studies presented by Viola et al. (2019) (see the citations of Viola et al., 2017; Caracciolo et al., 2017 at line 369). Viola et al. (2008) focused on seasonal soil moisture dynamics impacting on plant water stress by using a zero-dimensional bucket-filling model, while ignoring the topographical effect on the lateral distribution, and where the authors identify two seasons and set rainfall parameters arising from a Poisson process. The paper by Anderson et al. (2012) seems a bit on the boundary of the topic of rainfall seasonality. The remaining citations suggested are based on the Budyko approach, but do not focus on the assessment of rainfall seasonality.
Therefore, we are aware of the state of the art in the literature and here confirm that, actually, few studies (such that of Viola et al, 2008) have dealt in the past with rainfall seasonality issues. Only recently have we witnessed an increase in the number of studies dealing with that topic, and our submission is also heading in this direction. Unlike the few previous studies (such as the paper by Viola et al., 2008), our study proposes a new approach for assessing the impact of observed rainfall data on a water budget. In so doing, we generate new random daily rainfall data as input in a hydrological model (such as SWAT) under a Mediterranean climate. It is therefore fundamental to group rainfall seasons adequately to properly calculate the statistical parameters belonging to a Poisson process even when the user has a short-term rainfall data set.
We gave due consideration to this comment (please see Reply-3.1) and changed several parts of the Introduction (lines 69-117)

Other comments:
Line 47: “The amount of rainfall in each season can be suitably decomposed and simulated considering the following three main components.” It’s not clear to me how this statement fits in with the rest of the introduction. Why is intra-annual variability discussed at this point, when the focus of the study is on inter-annual variability of seasonality? I suggest the authors move this into the method section when discussing the Monte Carlo simulations for daily rainfall. Also, the representation of rainfall via a stochastic Poisson process (which this set of criteria is describing) should be associated with more foundational studies than those of Van Loon et al. 2014 and Feng et al. 2013 – this was introduced first by Rodriguez-Iturbe et al. 1987 “Some models for rainfall based on stochastic point processes” in PRSA and more widely disseminated in Rodriguez-Iturbe et al. 1999, PRSA.
REPLY-3.3. The parameters describing the intra-annual variability of rainfall identify the timing, duration, and magnitude of the rainfall seasons (intra-annual variability) that nevertheless change with time (inter-annual variability). We agree with this comment about the seminal paper by Rodriguez-Iturbe et al. (1987), but we did not cite it since it is actually embedded in the papers by van Loon et al. (2014) and Feng et al. (2013).

The presentation of Budyko’s curve as a conceptual and unifying framework is commendable, but it that it is too rushed. This may be a widely used concept in hydrological sciences, but it does not make a first appearance until the results section (starting on line 367!!) and need to be motivated better in the introduction and methods section.
REPLY-3.4. This is a good point and we thank this reviewer for that. Honestly, we should admit that presenting our outcomes even within Budyko’s framework is something that was discussed among us

only shortly before submitting the manuscript to HESS-D. In the revised paper Budyko's theory has been moved from Section 5.4 to Section 4.3 (lines 289-300)

Additionally, description for each of the "static" scenarios ("reference" "dry" and "wet") also only makes first appearance in the results section (lines 265-270) and need to be moved to the methods section.
REPLY-3.5. In this case, we prefer to keep this description as in the original manuscript, because it is based on the results rather than being an a-priori hypothesis.

SWAT model calibration has not been adequately described. While the performance is shown to be good at the monthly scale (line 141), there could still be compensating model parameters. It would be helpful to see a table of calibrated values for the list of model parameters in lines 137 – 141.
REPLY-3.6. This concern was raised also by Reviewer#1. Below we report our reply 1.2:
Nasta et al. (2017 STotEnv) calibrated nine model parameters by comparing measured and simulated monthly water yields recorded at the dam. Numerical simulations were run at the daily time step (the only time step allowed in SWAT). In this study, we followed the same criterion: we ran numerical simulations at the daily time step (rainfall was randomly generated at the daily time step) and aggregated the output fluxes at a monthly time resolution. We are aware that calibrating at the monthly time-scale might lead to a potential misfit between measured and simulated values at a daily time-scale (e.g. Adla et al., 2019, Water). However, our analysis is based on the monthly aggregation of fluxes and we analyzed seasonal patterns of monthly aggregates. In the light of the above comment, we added a new part at lines 182-188 to clarify this important point and why this misfit should not be viewed as relevant to our analysis. The reference to the paper by Adla et al. (2019) is also added.

Adla, S., S. Tripathi, M. Disse, 2019. Can we calibrate a daily time-step hydrological model using monthly time-step discharge data? Water 11, 1750; doi:10.3390/w11091750.

Assessing the impact of seasonal rainfall ~~seasonality~~ anomalies on catchment-scale water balance components

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Abstract. ~~Water~~ Although water balance components at the catchment scale are strongly related to annual rainfall ~~amount. Nonetheless,~~ , availability of water resources ~~availability~~ in Mediterranean catchments also depends ~~also~~ on rainfall seasonality. ~~Indeed, a high percentage of annual rainfall occurs between late fall and early spring and feeds natural and artificial water reservoirs. This amount of water stored in the mild-rainy season is used to offset rainfall shortages in the hot-dry season (between late spring and early fall).~~ Observed seasonal anomalies in historical records are ~~quite~~fairly episodic, but an increase ~~of~~in their frequency might exacerbate water ~~stress~~deficit or water excess if the rainy season shortens or extends its duration, e.g. due to climate change. ~~Hydrological models are useful tools to assess the impact of seasonal anomalies on the water balance components and this~~This study evaluates the sensitivity of water yield, evapotranspiration, and groundwater recharge ~~on~~to changes in rainfall seasonality by using the Soil Water Assessment Tool (SWAT) model~~. The study area is~~ applied to the Upper Alento River Catchment (UARC) in southern Italy where a long time- series of daily rainfall is available from 1920 to 2018. ~~To assess seasonality anomalies, we~~We compare two distinct approaches: *i)* a "static" approach~~ based on the Standardized Precipitation Index (SPI), and a "dynamic" approach that identifies the rainy season by considering rainfall magnitude, timing, and duration. The former approach rigidly selects~~, where three seasonal features~~,~~ (namely rainy, dry, and transition fixed-duration 4-month seasons~~, the latter being occasionally characterized by similar properties to~~) are identified through the standardized precipitation index (SPI); *ii)* a "dynamic" approach based on a stochastic framework where the duration of two seasons (rainy and dry seasons) varies from year to year according to a probability distribution. Seasonal anomalies occur when the transition season is replaced by the rainy or dry ~~periods. The "dynamic"~~season in the first approach and when season duration occurs in the tails of its normal distribution in the second approach~~, instead, is based on a time-variant~~

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~~duration of the rainy season and enables to corroborate the aforementioned results~~. Results are presented within a probabilistic framework. ~~A dry seasonal anomaly is characterized by a decrease of 241 mm in annual average rainfall inducing a concurrent decrease of 116 mm in annual average water yield, 60 mm in actual evapotranspiration and 66 mm in groundwater recharge. We~~We also show that the Budyko curve is sensitive to the rainfall seasonality regime in UARC by questioning the implicit assumption of a temporal steady~~-~~ state between annual average dryness and the evaporative index. Although the duration of the rainy season does not exert a major control on water balance, we ~~have been~~were able to identify ~~seasonal~~season-dependent regression equations linking water yield to the dryness index ~~over~~in the rainy season.

1. **Introduction**

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The rainfall regime of the Mediterranean climate is characterized by the alternation of wet and dry periods within the year, with ~~an~~ evident out-of-phase seasonal behavior of precipitation and temperature patterns. ~~Indeed, the majority of the~~Most annual ~~amount of~~ rainfall is concentrated in the late fall ~~and~~, winter ~~months~~, and early spring, while late spring, summer ~~is~~, and early fall are usually hot and quite dry. Rainfall seasonality plays a fundamental role in planning and managing water resources in countries subject to a Mediterranean climate.

~~Scarce~~Summer is characterized by water stress due to scarce rainfall supply, combined with high evapotranspiration ~~losses~~loss and ~~excessive~~ the seasonal peak in water consumption ~~of water (~~(comprising agricultural, industrial, and recreational uses, hydroelectric power generation, as well as ~~civil~~domestic uses ~~being~~, which are often ~~increased~~boosted by ~~the~~ tourism pressure~~) induces water stress during summer.~~). Therefore, it is necessary to store water during the rainy period to cope with the ~~"~~"uncertain~~"~~" duration of adverse water deficit conditions during the dry period. ~~Supply-water~~Water-supply infrastructures necessitate high investment costs that strongly depend on the expected balance between the amount of water supplied in the rainy period and the amount of water lost and consumed during the dry season. The amount of rainfall in each season can be suitably decomposed and simulated ~~considering~~on the basis of the following three main components: *i*) duration of the seasons; *ii*) occurrence probability of a daily rainfall event in each season; *iii*) mean depth of daily rainfall events in each season (Van Loon et al., 2014). A combination of the last two factors determines the rainfall magnitude in each season (Feng et al., 2013).

A very ~~low~~small or very ~~high~~large amount of water (exceeding a certain threshold value for a specified return period and duration) ~~that is~~ supplied ~~during the rainy period~~in each season can be interpreted as a seasonal precipitation anomaly and is usually observed episodically in a historical multi-decadal time-series of annual rainfall values. ~~The seasonal~~Seasonal precipitation anomalies ~~depend~~result mainly ~~on~~from a combination of the duration of the wet season and its rainfall magnitude. These two factors should be taken ~~in~~into due account when planning water-supply ~~water~~ infrastructures (Apurv et al., 2017). The most recent reports released by the Intergovernmental Panel on Climate Change (IPCC) warn ~~on~~of the projected increase in seasonal anomalies induced by global warming in the Mediterranean region, with a ~~remarkable~~considerable decrease in annual precipitation and warming-enhanced evapotranspiration associated with rather severe and prolonged droughts, as recently observed in southern Europe in 2003, 2015, and 2017 (Mariotti et al., 2008; Laaha et al., 2017; Hanel et al., 2018).

Studies ~~under way~~underway in the Upper Alento River Catchment (UARC) in southern Italy offer a good chance to understand the effects of ~~rainfall~~ seasonal rainfall uncertainty on water supply generation given the presence of a multi-purpose earthen dam (known as Piano della Rocca) constructed to regulate water for irrigation, ~~hydro-power~~hydropower generation, flood control, and drinking purposes. The main research question, also ~~solicited~~raised or prioritized ~~somehow~~in some way by local stakeholders in their decision-making processes, can be expressed as follows: "*What is the impact of seasonal rainfall ~~seasonality~~ anomalies on annual- average (or seasonal- average) water supply ~~and what happens if~~in UARC?*". This question is particularly relevant to hilly catchments similar to UARC within the ~~*Alento River*~~ Mediterranean region such that UARC could become a pilot area for dealing with some specific problems and carrying out paired-catchment ~~*(ARC) will experience several consecutive years of lower-than-expected rainfall events?*"~~analyses.

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~~To deal with at least the first part of the above research question, a prime objective is the quantification of the~~ This study therefore aimed to quantify the effects exerted by seasonal rainfall ~~seasonality~~anomalies on water balance components. With a view to ~~positive interactions~~coordinating interaction with stakeholders, end-users, and professionals, we performed this task by implementing the well-known and well-validated Soil Water Assessment Tool (SWAT) model ~~whereas a particular~~(Arnold et al., 1998). Particular attention is devoted to ~~the computation of~~computing water yield supplying the artificial reservoir bounded by the ~~"~~Piano della Rocca~~"~~ earthen dam in ARC (Romano et al., 2018). One of the strengths of our approach lies in the availability of long-term rainfall time-series (about a century of daily data) and detailed soil and land cover maps, enabling reliable catchment-scale model simulations. Reliable scenario-based projections are built to investigate whether the longer-than-average duration of the wet season implies a higher-than-average mean annual rainfall and consequently higher-than-average water yield. To investigate this issue, our research strategy couples the seasonal duration with daily rainfall occurrences and depths by using a Monte Carlo approach to obtain SWAT-simulated water balance components within a general probabilistic framework.

Many authors have attempted to quantify ~~the~~ rainfall seasonality ~~by~~ using different approaches (Ayoade, 1970; Markham 1970; Nieuwolt, 1974; Oliver, 1980; Walsh and Lawler, 1981; Zhang and Qian, 2003; Martin-Vide, 2004; Potter et al., 2005; Feng et al., 2013; de Lavenne and Andréassian, 2018). ~~The Precipitation Concentration Index~~The precipitation concentration index (PCI) proposed by Oliver (1980) is the most popular approach for quantifying the year-round precipitation distribution in a given study area (Raziei, 2018). Sumner et al. (2001) analyzed the spatial and temporal variation of precipitation seasonality over ~~the~~ eastern and southern Spain by using the seasonality index (SI). The SI ~~indicator~~ was also utilized ~~for examining~~to examine the spatial and temporal variability of precipitation seasonality in Greece (Livada and Asimakopoulos 2005), USA (Pryor and Schoof 2008~~)~~), and northern Bangladesh (Bari et al. 2016). Under the typical Mediterranean climate of Sardinia (Italy), Corona et al. (2018) used the SI ~~indicator~~ to evaluate the role of precipitation seasonality on runoff generation.

~~The goal~~Nonetheless, while PCI and SI are useful indexes to classify rainfall seasonality and the degree of ~~this study~~concentration of rainfall within the year, their implementation in a Monte Carlo framework is not straightforward. Therefore, we opted to characterize ~~the~~ rainfall seasonality and its anomalies by using the two approaches described as follows. A first approach, which is hereafter referred to as the static approach, is based on the analysis of the ~~Standardized Precipitation Index (SPI).~~standardized precipitation index (SPI) to define the duration of a wet season (4 months), a dry season (4 months) and a transition season (2 months from dry to wet phase plus 2 months from wet to dry phase) in UARC. In this approach, the drought anomaly is rigidly built with the artifact of extending the duration of the dry season to eight months by removing the transition season. The same criterion applies to a prolonged duration of the rainy season. The second approach, instead, exploits the seasonality characterization proposed by Feng et al. (2013) and can be viewed as a dynamic approach~~.~~ since the duration of the rainy season is time-variant (inter-annual variability) and can be stochastically generated with random duration values drawn from their statistical distribution. This second approach investigates what happens to the water budget if the duration of the rainy season becomes shorter-than-normal (i.e. rainfall scarcity) or longer-than-normal (i.e. rainfall excess). As far as we are aware, there is still a lack of knowledge about the effects of possible changes in rainfall seasonality on the water balance of a catchment subject to a Mediterranean climate, and the analyses presented in this paper ~~aims~~aim primarily ~~at contributing~~to contribute to fill this gap.

2. Study area and experimental analyses

The Upper Alento River Catchment (UARC) is situated in the Southern Apennines (Province of Salerno, Campania, southern Italy) and has a total drainage area of about 102 km^2~~.~~ (Fig.1). The ~~"~~Piano della Rocca~~"~~ dam is an earthen embankment with an impervious core that has been operating since 1995. The area consists mostly of relatively poor-permeable arenaceous-clayey deposits and secondarily of arenaceous-marly-clayey and calcareous-clayey deposits (Romano et al., 2018).

Please insert Fig. 1 here

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A weather station managed by the Italian Hydrological Service is located ~~in~~near the village of Gioi Cilento and provides a dataset of daily rainfall values covering the period 1920-2018 (about 90 years), with an interruption of ~~9~~nine years (1942-1950) ~~that straddled~~straddling World War II (Nasta et al., 2017). The ~~total (cumulative)~~ data set of annual ~~depth of precipitation~~rainfall sums derived from the daily rainfall time series ~~of the entire available period is characterized by~~has a mean of 1,229.3 mm, ~~a~~ while other metrics (median ~~value of 1,198.3 mm, a,~~ standard deviation ~~(Std. Dev.) equal to 295.9 mm,~~ and ~~a~~ coefficient of variation ~~(CV) equal to 24.1%; the mean and median values~~) are ~~quite close indicating that this available dataset follows a normal distribution closely.~~reported in the last row of Table 1. The same statistics are also summarized for rainfall depths in each month of the year. The variability exhibited by the monthly time series of rainfall depths is ~~instead summarized in Table 1 and~~also depicted in Figure ~~1~~2, denoting a typical Mediterranean seasonal cycle. A large amount of precipitation occurs in the months from October to March, a period commonly identified as a wet period of ~~a~~the hydrological year, and accounts for about 68% of the ~~mean~~ annual mean rainfall (i.e. 834.9 mm over 1,229.3 mm) (see Table 1 and Figure ~~1~~2). November is the wettest month with an average monthly rainfall ~~depth~~ of ~~152.2~~166.9 mm (about 14% of mean annual rainfall). In contrast, lower ~~means of~~mean monthly rainfall ~~depth~~depths are concentrated from April to September, which ~~is~~ commonly ~~identified as~~identify a dry period of ~~a~~the hydrological year, with a cumulative rainfall ~~depth~~ over this period of ~~343.7~~394.5 mm with respect to the annual mean ~~yearly value~~ of 1,229.3 mm, ~~and~~ hence representing about ~~31~~32% of ~~the~~ mean annual rainfall. July is the driest month with a ~~mean~~ monthly mean rainfall ~~depth~~ of ~~17.6~~29.8 mm (i.e. ~~1.6~~2% of ~~the yearly~~mean annual rainfall ~~depth~~).

Please insert Fig. 2 here

~~*Please insert Fig. 1 here*~~

Please insert Table 1 here

Within the monitoring activities of the MOSAICUS (MOnitoring and modeling Soil–vegetation–atmosphere processes in the Alento river basin for Implementing adaptation strategies to Climate and land USe changes) project (Nasta et al.,

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2013; Romano et al., 2018), an automated weather station was installed in 2004 close to the village of Monteforte Cilento and equipped with sensors for ~~precipitation~~monitoring rainfall, wind speed and direction, air temperature and relative humidity, and solar radiation, to record ~~these~~such meteorological variables at 15 min intervals~~. The data set of daily rainfall values (1920-2018) recorded at the weather station of Gioi Cilento will be used to assess rainfall seasonality.~~ (Nasta et al., 2019). The statistical distributions of weather data recorded at the weather station of Monteforte Cilento (2004-2018) will be used to calculate potential evapotranspiration as described in Section 3.

In this study, we used the most recent available land-use map drawn ~~on~~up in 2015 by using second-level CORINE (Coordination of Information on the Environment) Land-Cover classes (CORINE 2006 land cover dataset; http://www.eea.europa.eu): forest, arable land (annual crops), permanent crops (orchards, vineyards, olive groves, and fruit trees), pasture, urban fabric, and water bodies. Forest (evergreen and deciduous trees, and multi-stem evergreen sclerophyllous Mediterranean shrubs) and agricultural (arable land, permanent crops, and orchards) cover about 70% and 20% of the catchment, respectively (Nasta et al., 2017). A five-meter resolution Digital Terrain Model (DTM) was used to generate the hydrographic network and a soil-landscape units map is used to depict soil attributes in UARC (Nasta et al., 2018).

3. Parameterization of the SWAT Model

The Soil Water Assessment Tool (SWAT) is a bucket-type, semi-distributed hydrological model operating on a daily time scale and at a catchment spatial scale (Arnold et al., 1998). The main components of the water balance equation are the daily change in water storage (ΔWS) as affected by rainfall (R), actual evapotranspiration (ET_a), groundwater recharge (GR), and water yield (WY). Water yield is given by the contribution of surface runoff, groundwater circulation, and lateral flow within the soil profile, and is partially depleted by transmission losses from tributary channels and water abstractions. All variables are expressed in units of mm of water height.

The boundary forcings areSWAT requires as input rainfall (*R*) and potential evapotranspiration (ET_p) computed ontime series at a daily basis. SWATscale and is based on the concept of Hydrological Response Unitshydrological response units (HRUs), which are areas identified by similarities in soil, land cover, and topographic features. A 5-m Digital Elevation Model (DEM), where hydrological processes are represented by a lumped schematization. The five-meter DTM of the study area was used to determine the catchment boundaries, the hydrographic network, and thirteen distinct HRUs. Catchment-lumped parameters are assigned to each HRU through look-up tables. KnownBy using the available soil-landscape unit map, the input parameters were assigned according to the model set--up as presented in Nasta et al. (2017). Nine parameters were calibrated to achieve the best model fit between simulated and measured monthly water yield data recorded from 1995 and 2004 (Nasta et al., 2017). Such hydrological parameters include the soil evaporation and compensation factor, plant uptake compensation factor, Manning's value for overland flow, the baseflow recession constant (groundwater flow response to changes in recharge), groundwater delay time, groundwater "revap" coefficient (controlling water that moves from the shallow aquifer into the unsaturated zone), Manning's coefficient for the main channel, effective hydraulic condition in the main channel alluvium, and bank storage recession curve. Model performance proved to be satisfactory at monthly time scale.the bank storage recession curve. Model performance proved to be satisfactory at a monthly time scale. We ran numerical simulations at a daily time step (rainfall was randomly generated at a daily time step) and aggregated the output fluxes at a monthly time resolution. Although there is evidence in the body of scientific literature of a potential misfit between measured and simulated water yield values at a daily time-scale when calibrating a model with data at a monthly time resolution (Adla et al., 2019), we are confident that our results and conclusions will not be affected by this drawback. Our analysis is based on the monthly aggregation of fluxes and is aimed at analyzing seasonal patterns of monthly aggregates.

This study is based on modellingmodeling scenarios implemented in SWAT through a Monte Carlo approach, where each simulation is 3-yearthree years long. Results from the first 2two-year warm-up period are discarded, while water balance components simulated for the third year are stored for subsequent analysis. Initial soil water storage is set as field capacity. ~~The rainfall data will be~~The model simulations of the first two years are disregarded in order to erase the impact of the initial (unknown) soil moisture values set in the soil domain. We point out that initial soil water content set at field capacity can be considered a realistic situation in winter under the Mediterranean climate. The rainfall data are generated for the static and dynamic approaches (described below) using a probability setting calibrated on daily rainfall values recorded at the Gioi Cilento weather station (1920-2018). ~~The~~ Mean and standard deviation of the meteorological data (wind speed, air temperature and relative humidity, and solar radiation) recorded at the second automated weather station (close to the village of Monteforte Cilento) ~~will be used for statistical analysis at monthly time scale: results will be~~are calculated each month. Daily potential evapotranspiration data were calculated by using random values of weather data drawn from their normal distribution in each month of the year (Allen et al., 1998). Results were provided as input to SWAT ~~in order~~ to randomly generate daily ~~reference~~potential evapotranspiration by using the Penman-Monteith equation (Allen et al., 1998).

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4. Determination of rainfall seasonality

4.1. Static approach based on the SPI drought index

The intra-annual rainfall regime under a Mediterranean climate can be characterized through the ~~partitions~~distribution of annual rainfall depth among different seasons (Paz and Kutiel, 2003; Kutiel and Trigo, 2013). The seasonal pattern occurring in the study area is ~~based~~here characterized by analyzing the distribution of the standardized precipitation index (SPI) on a long-term monthly rainfall time series ~~through the Standardized Precipitation Index (SPI).~~. The SPI is a probability index developed to classify rainfall anomalies and often employed as an indicator of potential (meteorological) droughts over many time scales (McKee et al., 1993; Hayes et al., 1999). ~~The computation~~Computation of the SPI should rely on long-term rainfall datasets (e.g. 30 years, according to climatological standards), and is usually obtained by projecting a Gamma distribution fitted on rainfall depths cumulated on 1, 3, 6, 12, 18, or 24 months (referred to as SPI-1, SPI-3, SPI-6, SPI-12, SPI-18, or SPI-24, respectively) into a standardized normal distribution. ~~Short~~The short-term SPI (e.g. 3-month time scale) can provide useful information for crop production and soil moisture supply, while the long-term SPI (e.g. 12- or 24-month time scale) can give insights on water availability for groundwater recharge. Negative SPI- values indicate lowerdrier-than-expected rainfall, whereas positive SPI- values refer to wetter-than-expected months. To quantify the degree of departure from median conditions, McKee et al. (1993) proposed a rainfall regime classification. Since the SPI is given in units of standard deviation from the standardized mean, this statistical index enables also the precipitation anomaly to be identified through the magnitude of its value: values ranging from -–0.99 to +0.99 are considered near normal, from +1.00 to +1.49 (or from -–1.49 to -–1.00) indicatesindicate moderately wet (or moderately dry) periods, from +1.50 to +1.99 (or from -–1.99 to -–1.50) very wet (or very dry) periods, and above +2.00 (or below -–2.00) extremely wet (or extremely dry) periods. Therefore, the extent of SPI departure from the mean (i.e. from the zero value) gives a probabilistic measure of the severity of a wet (if positive) or dry (if negative) period. By exploiting the properties of the (standard) normal distribution, the probabilities to obtainof obtaining SPI- values greater than +1, +2, and +3 (or lowerless than -–1, -–2, and -–3) are 15.990%, 2.28% and 0.13514%, respectively.

In order toTo emphasize the seasonal cycle of intra-annual rainfall patterns within a probabilistic framework, we slightly modifiedused the common SPI application-1 by fitting the Gamma distribution on all monthly rainfall depths, i.e. pooling together observations from all months in each year. In such a way, the months characterized by SPI-1 values below, around or above the zero line can be assumed to belong to the dry, transition or wet seasons, respectively.

4.2. Dynamic approach based on the duration of the wet season proposed by Feng et al. (2013)

According to Feng et al. (2013), the Dimensionless Seasonality Indexdimensionless seasonality index (DSI) is based on the concept of relative entropy and quantifies the rainfall concentration occurring in the wet season. The DSI is zero when the average annual rainfall is uniformly distributed throughout the year and maximized at 3.585 when maximum average annual rainfall is concentrated in one single month (Pascale et al., 2016); see the Appendix for details. Feng et al. (2013) proposed to describe the rainfall seasonality through the following three components: annual rainfall depth (magnitude), centroid (timing), and spread (duration) of the wet season (see also Pascale et al., 2015; Sahani et al., 2018). ~~Following this framework, the hydrological year is assumed to start from the driest month~~As described in Section 5.2 and ~~proceeds for the subsequent 12 months, rather than starting at a prescribed month (e.g. on April,~~ according to ~~a conventional way). Specifically~~appropriate statistical tests, we ~~assumed~~found that ~~the duration of the~~ a normal distribution can reasonably describe the 90 wet season ~~follows a normal distribution, with mean and standard deviation estimated from the 90~~ durations obtained ~~for each year~~ by applying to the ~~Gioi Cilento~~observed rainfall time series the procedure proposed by Feng et al. (2013~~)~~), and briefly ~~resumed~~summarized in the Appendix. Thus, each hydrological year will consist of the alternation of only two seasons: the wet season with a duration that is randomly generated by a normal distribution with mean and standard deviation estimated on the Gioi Cilento time series, and a dry season in the subsequent months of the year.

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4.3 Set~~-~~-up of Monte-Carlo rainfall scenarios in SWAT

~~Rainfall seasonality~~Seasonal rainfall anomalies, although episodic, can affect the water balance components at the catchment scale. As suggested by Domínguez-Castro et al. (2019), the impact of such anomalies can be quantified within a probabilistic framework. For the Upper Alento River Catchment (UARC), we evaluated the effects of seasonal anomalies by running SWAT simulations with synthetic rainfall time series considering different hypotheses (scenarios) of alternations of seasons, according to the "static" and the "dynamic" approaches described above. In each season, we assumed that rainfall evolution in time can be represented by a stochastic Poisson point process of daily rainfall occurrences, with daily rainfall depth following a proper probability distribution~~.~~ (Eagleson, 1972; Rodríguez-Iturbe et al., 1987; Veneziano and Iacobellis, 2002). Synthetic rainfall time series were then generated, keeping constant parameters of the Poisson process and daily rainfall parent distribution in each season.

A preliminary analysis was conducted to investigate the best parent distribution for observed rainfall daily depths. With this aim, we used the L-moment ratios diagram proposed by Hosking (1990) (see also Vogel and Fennessey, 1993) as a diagnostic tool. Results are shown in Figure ~~2~~3 where the L-skewness and L-kurtosis computed on the time series left-censored with a threshold of 3 mm (large filled circle) is compared with the theoretical expectation of the same L-moment ratios for several probability distributions commonly adopted in statistical hydrology. ~~It is apparent that~~An ideal candidate as parent distribution ~~is~~seems the Generalized Pareto distribution (GPd), although it is also ~~worthwhile noticing~~worth noting that sample estimation of L-skewness and L-kurtosis (0.3437, 0.1706) is very close to the expected values for ~~an~~ exponential distribution (1/3, 1/6). As ~~a~~ visual support ~~of~~for this preliminary analysis, the exponential probability plot in Figure ~~3~~4 compares the empirical cumulative distribution function F(x) of the observed time series (circles) with the fitted GPd (dashed line) and the fitted exponential distribution (continuous line). ~~It is apparent that the~~The two models are very close to each other for the whole body of observation, with only a slight departure of the GPd from the straight line ~~charactering~~characterizing the exponential distribution due to a very ~~light~~slight right tail. ~~These evidences made~~This evidence gave us ~~confident in adopting~~the confidence to adopt the single-parameter exponential model as parent distribution for series partitioned according to the seasons defined above, thereby reducing ~~in such a way~~ the uncertainty related to the additional shape parameter of the GPd. Finally, it is worthwhile mentioning that both distributions shown in Figure ~~3~~4 were fitted by applying ~~the Multiple-Threshold Method (MTM) by Deidda~~Deidda's (2010) multiple-threshold-method (MTM) on a range of thresholds from 2.5 to 12.5 mm to prevent biases due to very low records and data discretization (Deidda, 2007). The MTM was then applied to estimate the exponential parameter η (mm) and the probability occurrence of rainy days λ (d^{-1}) for each season considered ~~season~~.

For each scenario pertaining to either the "static" or "dynamic" approach, we generated 10,000 equi-probable realizations of synthetic daily rainfall time series, each ~~3-year~~three years long, according to a stochastic Poisson point process model. In each ~~modelling~~modeling scenario, the synthetic time series was then used as input ~~of~~for the SWAT model to evaluate the effects on the water balance components in UARC. ~~The~~As anticipated in Section 3, the first two years represent warm-up simulations and were thus discarded, while only results for the third year were stored for subsequent analyses presented in the next section. ~~For the former approach the alternation of seasons was fixed, as already pointed out, while for the "dynamic" approach the duration of wet season in each year was randomly drawn~~

from a normal distribution (with mean equal to 2.71 months and standard deviation equal to 0.28 months, estimated from the Gioi Cilento daily rainfall dataset).

Please insert Fig. 2 here

Please insert Fig. 3 here

Please insert Fig. 4 here

To further evaluate the hydrologic behavior of the study catchment, an issue deserving more detailed attention is the assessment of the sensitivity of water balance to rainfall seasonality. With this aim, we refer to the Budyko framework (Budyko, 1974), which has been extensively applied to relate water components in different climatic contexts worldwide, including the Mediterranean climate (see e.g. Viola et al., 2017, Caracciolo et al. 2017). Specifically, the Budyko framework relates the evaporative index (ET_a/R) to the dryness index (ET_p/R) computed at an annual time scale in terms of “available water” (i.e., rainfall R). Potential evapotranspiration, ET_p, is limited by either energy supply (for the dryness index less than or equal to one) or water supply (for the dryness index greater than one), and therefore the Budyko space has two physical bounds dictated by either the atmospheric water demand ($ET_a \leq ET_p$) or the atmospheric water supply ($ET_a \leq R$). The first bound is the energy limit (or demand limit, i.e. the 1:1 line corresponding to $ET_a=ET_p$) implying that actual evapotranspiration cannot exceed potential evapotranspiration. The second bound is the water limit (or supply limit, i.e. the horizontal line corresponding to $ET_a=R$) implying that actual evapotranspiration cannot exceed precipitation when the dryness index is greater than one (i.e. $ET_p/R>1$).

5. Results and discussion

5.1. Static approach for assessing rainfall seasonality

ObservedThe observed temporal evolution of SPI-6 in our 90-year time series (see greygray bars in Fig. 45) highlights prolonged droughts in betweenamongst the 1980s and the 1990s and prolonged wet periods in the last decade when SPI-6 values above the threshold +2 occurred in 2008, 2010, and 2012. Yet, by splitting the frequency distribution of

~~the~~ SPI-6 values ~~in~~into two 45-year sub-groups, ~~one in~~ we can observe that the last 45-year period is characterized by a drier climate compared to the first 45~~ years and a second one~~-year period. Specifically, in the ~~last 45 years, we observe a general drying trend. In the~~ first sub-group the probabilities ~~to obtain~~of obtaining SPI-6>+1 and SPI-6~~<-~~<–1 are 17.9% and 7.6%, respectively. In contrast, in the second sub-group there is a general increase ~~of~~in negative SPI-6 values ~~by turning~~: the probability ~~into 11.9% to obtain~~of obtaining SPI-6>+1 becomes 11.9% and ~~19.3% to obtain get~~that of obtaining SPI-6~~<-~~<–1~~.~~ 19.3%. By analyzing daily rainfall datasets recorded at 55 weather stations located in the region of Basilicata ~~Region nearby~~near UARC (characterized by similar climatic conditions), Piccarreta et al. (2013) observed a general decreasing trend in the mean annual rainfall over the period 1951–2010 mainly due to the autumn-winter decrease ~~of~~in precipitation.

Please insert Fig. 5 here

~~*Please insert Fig. 4 here*~~

We now discuss ~~now about~~ the results pertaining to the calculation of the seasonal pattern of SPI-1 values. Rainfall seasonality under a Mediterranean climate can be assumed to be roughly represented by the alternation of two ~~6~~six-month seasons, characterized by positive and negative SPI-1 values (wet and dry season, respectively) (Rivoire et al., 2019). The temporal evolution of the SPI-1 values is represented by the ~~grey~~gray bars in Fig. ~~5a~~6a and highlights the seasonal cycle within each year, whereas their 12-month moving average (magenta line in Fig. ~~5a~~6a) oscillates around the zero~~-~~ value with prolonged dry periods ~~in between~~during the 1980s and ~~the~~ 1990s and prolonged wet periods ~~between~~in the 2000s and ~~the~~ 2010s. Fig. ~~5b~~6b shows the box and whiskers plots of the SPI-1 values for each month of the year, thus depicting the monthly distribution of this index throughout the available recorded period. The median SPI-1 values (central red line in the blue boxes) are negative only from May to August and positive from September to April, even though the whiskers (identified by the two lines at the 25th and 75th percentile) denote the presence of ~~a~~ relatively large variability in almost all months. ~~A closer~~Closer inspection of this graph enables one to identify three main seasonal features: *i*) a dry period from May till August with median values below zero; *ii*) a rainy period from

November till February with median values above zero; *iii*) two transition periods from wet to dry (March and April) and from dry to wet (September and October) with median values near zero. We are aware that the median values in March, April, and October of the transition season are above zero, rather than "near" zero, but we ~~remind~~recall that the Mediterranean climate in UARC is sub-humid mainly due to orographic influences. However, this approach ~~can be considered~~is intrinsically a "static" procedure since the subdivision of the twelve months ~~in~~into three groups is rigid even though months in the transition periods ~~are characterized by the highest SPI-values~~have high variability~~.~~ in SPI-1 values. This outcome refines the initial working hypothesis of seasonal alternation of two semesters~~ with random durations~~.

Please insert Fig. 6 here

~~*Please insert Fig. 5 here*~~

The frequency distributions of the SPI-1 values computed over the rainy, dry, and transition seasons are illustrated in Fig.~~5c-5d-5e~~6c-6d-6e. The wet season (depicted by the blue histograms) is characterized by probabilities ~~to have~~of having SPI-1 values greater than 0, +1, +2, and +3 of 80.~~6~~60%, 30.50%, 1.~~9~~90%, and 0.~~3~~30%, respectively. The dry season (depicted by the red histograms) is associated with SPI-1 values lower than 0, ~~-~~–1, ~~-~~–2, and ~~-~~–3 with probabilities of 78.~~1~~10%, 31.~~1~~10%, 0.56% and 0.~~1~~10%, respectively. Conversely, we warn that probabilities ~~to have~~of obtaining positive SPI-1 values in the transition season are ~~of~~ 63.~~3~~30% instead of the expected 50% if the hypothesis ~~was~~were "perfectly true". ~~We therefore~~Therefore, we considered three different scenarios, each with fixed and recurrent alternation of seasons during the hydrological year: *i*) a "reference scenario" with a ~~4~~four-month wet season (NDJF), a ~~4~~four-month dry season (MJJA), and a ~~4~~four-month transition season (MA from wet to dry and SO from dry to wet); *ii*) a "dry scenario", which mimics an extreme drought anomaly, characterized by a prolonged ~~8~~eight-month dry season (from March to October) and abrupt alternations with the ~~4~~four-month wet season (NDJF), without any transition season; *iii*) a "wet scenario", which mimics an extreme rainy anomaly, characterized by a prolonged ~~8~~eight-month wet season (from September to April) and abrupt alternations with the ~~4~~four-month dry season (MJJA), again with no transition season.

In light of the ~~aforementioned~~above results, the two Poisson parameters (η and λ) describing daily rainfall values were calculated for each of the three seasons in the “reference scenario” and ~~they are~~were then also used ~~for developing~~to develop synthetic simulations of rainfall time series in the “dry” and “wet” scenarios (see Table 2).

Please insert Table 2 here

5.2. Dynamic approach for assessing rainfall seasonality

The centroid of the monthly rainfall distribution measured at the Gioi Cilento weather station (in the 90 years between 1920 and 2018) indicates that the wet season is centered in the second half of December, while its average duration is about 5.44 months (see Fig. ~~6~~7). Nonetheless, it is worth noting the occurrence of a few extreme situations: the severe drought ~~spell~~ recorded in 1985 caused a minimum duration of about ~~4~~four months of the rainy period, while the year 1964 registered a maximum duration of about 7.0 months. The term “dynamic” used for this approach stems mainly from the fact that the duration of the rainy period is time-variant throughout the years.

~~*Please insert Fig. 6 here*~~

~~The Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1975) is used to evaluate possible decreasing, increasing, or absence of temporal trends on the DSI (Feng et al., 2013) or the seasonality index (SI) proposed by Walsh and Lawler (1981). This test did not highlight significant trend on DSI and SI at 0.05 significance level (z_c-values of -0.0027 and 0.0030, respectively). The stationarity in time of DSI (red line) and SI (green line) is also apparent from a perusal of Fig. 7, where the linear regressions (dashed and dotted for DSI and SI, respectively) are characterized by very weak downward slopes.~~

Please insert Fig. 7 here

The dimensionless seasonality index (DSI) and the seasonality index (SI) were computed for the Gioi Cilento time series according to procedures proposed by Feng et al. (2013) and by Walsh and Lawler (1981), respectively. The Mann-Kendall nonparametric test (Mann, 1945; Kendall, 1975) was then applied to evaluate possible decreasing, increasing, or absence of temporal trends on these indexes, and revealed that the null hypothesis of absence of trend cannot be neglected at the 0.05 significance level for both indexes. The stationarity in time of the DSI (red line) and SI (green line) is also apparent from a perusal of Fig. 8, where the linear regressions (dashed and dotted for the DSI and SI, respectively) are characterized by very weak downward slopes.

Please insert Fig. ~~**Under the “dynamic” approach, we consider**~~*8 here*

As described in Section 4.2, the dynamic approach assumes the alternation of only two seasons (wet and dry) with random durations of the rainy period. Figure ~~8a~~9a shows the time series of the 90 durations of the wet season estimated ~~duration of the wet season in each year,~~ with the procedure proposed by Feng et al. (2013), while their frequency distribution is plotted in Fig. 9b. We then applied the Lilliefors statistical test ~~has verified at~~(Lilliefors, 1967) to the null hypothesis of normality for the estimated wet durations obtaining a *p*-value of 0.327, meaning that the null hypothesis cannot be rejected with the commonly adopted 5% significance level~~ that observed data (Fig. 8b) belongs to~~. For each hydrological year, we thus generate a duration of the wet season from a normal distribution ~~(Lilliefors, 1967). The~~with the same mean and standard deviation of the Gioi Cilento time series (with a mean of 2.71 months and standard deviation of 0.28 months), while the dry seasons were consequently obtained as the complement in the same year to the wet seasons. In this case, the two Poisson parameters (η and λ) for modeling daily rainfall values were computed for the wet and dry seasons (Table 3).

Please insert Fig. 9 here

~~*8 here*~~

Please insert Table 3 here

5.3. Effects of seasonal rainfall ~~seasonality~~ anomalies on water balance ~~by~~when using the static approach

The results obtained from the three scenarios pertaining to the ~~“~~static~~”~~ approach are presented using the descriptive statistics of the water balance components at the annual time scale obtained from 10,000 SWAT simulation runs (Table 4). ~~Reference~~The reference scenario represents the normal situation with three seasons (dry, transition, and wet). Even though the range of annual rainfall values is relatively large, the coefficient of variation (CV) is only 14%, implying that very low and very high ~~(outliers)~~ annual rainfall depths (outliers) occur occasionally. The water balance components, namely water yield (*WY*), actual evapotranspiration (ET_a), and groundwater recharge (*GR*), represent ~~averagely~~on average 35%, 49%, and 16% of the annual mean rainfall depth (*R*=1,229 mm). The annual rainfall depths for the other two scenarios (only two seasons without the transition season) shift down to 988 mm (dry scenario) and up to 1,393 mm (wet scenario~~) and consequently affect~~), thus affecting the water balance. When the dry season lasts ~~8~~eight months (dry scenario), water yield, actual evapotranspiration, and groundwater recharge decrease by 116 mm, 60 mm, and 66 mm, respectively, when compared to the reference scenario.

Please insert Table 4 here

In contrast, when the wet season lasts ~~8~~eight months (wet scenario), the water yield, actual evapotranspiration, and groundwater recharge increase by 93 mm, 21 mm, and 54 mm, respectively, when compared to the reference scenario. Water yield, actual evapotranspiration, and groundwater recharge represent ~~averagely~~on average 32%, 55%, and 13% of the annual rainfall depth in the extreme dry season (dry scenario~~)~~), and 38%, 45%, and 18% of annual rainfall depth in the extreme wet season (wet scenario).

~~The decomposition~~Decomposition of the annual results into the seasonal components ~~highlight~~highlights other interesting features that are ~~showed~~shown in Fig. ~~9 (boundary~~10 (rainfall and potential evapotranspiration forcings) and in Fig. ~~10~~11 (main water balance components). For the reference scenario the seasonal rainfall depth is 201 mm, 436 mm, and 593 mm for the dry, transition, and wet seasons, respectively, representing 16%, 35%, and 48% of the total annual rainfall (see Fig. ~~9a~~10a). Water yield depths span from 44 mm during the dry season to 251 mm during the rainy season (see Fig. ~~10a~~11a). Almost 60% of annual water yield occurs over the wet season, about 30% in the transition season, and about 10% in the dry season. In contrast, the actual evapotranspiration depths are higher than rainfall depths in the dry season (269 mm) and lower than rainfall depths during the transition (226 mm) and rainy (110 mm) seasons (see Fig. ~~10a~~11a).

~~*Please insert Fig. 9 here*~~

Please insert Fig. 10 here

Please insert Fig. 11 here

Over the dry scenario (see ~~Fig. 9b~~Figs. 10b and ~~10b~~11b), the months belonging to the transition season become drier-than-normal. The total rainfall depths over the dry and wet seasons are 397 mm and 590 mm, respectively, whereas the extreme drought anomaly ~~causes~~induces precipitation loss only in the dry season with a ~~consistent~~considerable decrease of 239 mm of rainfall depth (Fig. ~~9b~~10b). The consequences of this situation on the average water balance components in the prolonged dry season lead to significant deficits (Fig. ~~10b~~11b). Water yield loss ~~in~~over the dry season is 93 mm, which represents 50% of water yield obtained ~~in~~for the dry and transition seasons in the reference scenario. The wet season (from November to February) provides about 590 mm of water yield per year. The water ~~lost~~loss by actual evapotranspiration is limited and represents only 10% of ET_a obtained ~~in~~for the dry and transition seasons in the reference scenario (Fig. ~~10b~~11b).

In the wet scenario (see Fig. ~~9c~~10c and Fig. ~~10c~~11c), the months belonging to the transition season ~~turn~~become wet (8 wet months and 4 dry months). Total rainfall depths in the dry and wet seasons are 200 mm and 1,193 mm (Fig. ~~9c~~10c). Rainfall depth increases by 164 mm in the wet season (+14% ~~than the one~~compared with that obtained in the wet and transition seasons in the reference scenario). Water yield gain in the wet season is 89 mm which represents 20% of water yield obtained in the wet and transition seasons in the reference scenario (Fig. ~~10c~~11c). The water lost by actual evapotranspiration is negligible.

5.4. Effects of seasonal rainfall ~~seasonality~~ anomalies on water balance ~~by~~when using the dynamic approach

The second approach ~~for~~to assessing the effect of rainfall seasonality extremes on water balance components is based on the stochastic generation of the wet season durations from their normal distribution (see Fig. ~~8b~~9b). This approach helps classify the results within a probabilistic framework according to the following rainy period duration classes: 3-4 months, 4-5 months, 5-6 months, 6-7 months, 7-8 months. Seasonal extremes (3-4 months and 7-8 months) have very low ~~occurrence~~ probabilities of occurrence (0.~~6~~60% and 0.~~3%).~~30%, respectively). Nonetheless, it is interesting to analyze the effect of rainfall variability on water yield (*WY*), actual evapotranspiration (ET_a) and groundwater recharge (*GR*). The most probable (62%) situation occurs when the rainy period lasts 5-6 months. Under these circumstances, the mean annual rainfall depth is 1,275 mm, whereas *WY*, ET_a, and *GR* represent 35%, 49%, and 16% of annual average rainfall depth, respectively. These percentages are ~~the same~~very close to those observed in the reference scenario of the static approach. If the wet season shortens by one month (23% probability), the mean annual rainfall depth decreases by 62 mm, whereas water yield depth by 33 mm ~~(-~~(–7%). In contrast, if the wet season is made up of 6-7 months (14% probability), the ~~mean~~ annual mean rainfall depth increases by 51 mm and water yield by 27 mm (+6%).

Extreme dry and extreme wet situations reflect similar results obtained from the dry and wet scenarios presented above. A prolonged drought ~~spell~~ (i.e. ~~lasting~~rainy period only 3-4 months long) leads to an average rainfall loss of 130 mm per year inducing ~~a consistent~~an appreciable annual decrease in both water yield ~~(-~~(–68 mm) and groundwater recharge ~~(-~~(–30 mm). A prolonged wet season (i.e. lasting 7-8 months), instead, causes ~~an~~ average rainfall to gain approximately 108 mm per year, ~~hence~~ yielding annual increases in both water yield (+59 mm) and groundwater recharge (+12 mm). It is worth noting that the duration of the rainy period does not seem to exert a major control on the water balance. ~~The~~ Pearson’s linear correlation coefficients between duration and average annual rainfall, water yield, and actual evapotranspiration are 0.22, 0.20, and 0.11, respectively.

Please insert Table 5 here

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~~**To further evaluate the hydrologic behavior of the study catchment, an issue deserving to be addressed with some more details is to assess the sensitivity of water balance to rainfall seasonality. We refer to the Budyko framework (Budyko, 1974), which has been**~~*Please insert Fig. 12 here*

Assuming~~ applied to relate water components in different climatic contexts worldwide, including the Mediterranean climate (see e.g. Viola et al., 2017, Caracciolo et al. 2017). Specifically, the Budyko framework relates the evaporative index (ET_a/R) to the dryness index (ET_p/R) computed at annual time scale in terms of "available water" (i.e., rainfall R). Potential evapotranspiration, ET_p, is limited by either energy supply (for the dryness index less than or equal to one) or water supply (for the dryness index greater than one) and therefore the Budyko space has two physical bounds dictated by either the atmospheric water demand ($ET_a \leq ET_p$) or the atmospheric water supply ($ET_a \leq R$). The first bound is the energy limit (or demand limit, i.e. the 1:1 line corresponding to $ET_a = ET_p$) implying that actual evapotranspiration cannot exceed potential evapotranspiration. The second bound is the water limit (or supply limit, i.e. the horizontal line corresponding to $ET_a = R$) implying that actual evapotranspiration cannot exceed precipitation when dryness index is greater than one (i.e. ET_p/R>1).~~

~~*Please insert Fig. 11 here*~~

~~By assuming~~ that the long-term mean annual precipitation can be partitioned into the mean annual actual evapotranspiration and mean annual water yield, according to the Budyko framework we assume that larger values of the dryness index (drier climate conditions; $ET_p/R > 1$) induce a greater proportion of rainfall that is partitioned to ET_a. In contrast, data on the left-hand side of the Budyko curve will be characterized by a greater proportion of rainfall that is partitioned to water yield. Fig. ~~11~~12 shows the Budyko plot of the dryness index (ET_p/R) versus the evaporative index (ET_a/R) together with the Budyko curve (solid garnet line). In this plot we ~~have inserted~~depict the data points (colored dots) for the five different durations of the rainy period in UARC obtained by the dynamic approach. ~~A~~The first comment to be made is that all of these data points gather within the energy-limited region of the Budyko plot, with the longest rainy period (blue dot) favoring conditions of greater discharges (evaporative index ~~of~~ ET_a/R=0.45) and the shortest rainy period (droughts indicated by the red dot) inducing higher evapotranspiration fluxes (evaporative index

~~of~~$ET_a/R=$ 0.54). ~~This~~The latter situation ~~highlights~~shows that on average the Upper Alento River catchment is characterized by ~~a~~ relatively good storage of soil-water made possible by the hydraulic properties of the soils and the large portion of shrub spots and forest areas (mostly ~~chestnut~~ deciduous chestnut forests and olive orchards), together with a good amount of annual precipitation in a hilly and mountainous zone ~~of~~in southern Italy. However, ~~ET_p and ET_a are not almost equivalent and one can even note~~it may also be noted that all of these data points cluster below the Budyko curve (Williams et al., 2012). The observed departure below the Budyko curve ~~can~~may be due to ~~a number of~~several reasons. Allowing for the Budyko assumptions for water balance, the present study refers to a long time scale (90 years), but a relatively small spatial scale since UARC has a drainage area of 102 km^2 ~~and therefore local conditions and controlling factors might exert some effects on the water budget calculations. Actually~~. In fact, rainfall seasonality (i.e. intra-annual variability) ~~can~~may be just ~~be~~ one of the major factors ~~having~~that could have led to a departure from the Budyko curve. The typical Mediterranean climate, which is characterized by ~~a~~ precipitation being out-of-phase with potential evapotranspiration, is also singled out as a cause of the deviations we ~~have~~ observed in our case study from the Budyko curve (Milly, 1994). Normal situations, characterized by a wet season lasting 5-6 months (green dot), lead to ~~partition~~ rainfall being partitioned into 49% ET_a, as indicated by the evaporative index value of 0.49. We hereby recall that this study is based on the assumption that the catchment response is not affected by human interferences and their feedbacks (land-use change, change in soil hydraulic properties, enhanced evapotranspiration induced by global warming, etc.), but only by changes in rainfall seasonality ~~that~~which, of course, can undermine Budyko's implicit assumption of temporal steady-state (Feng et al., 2012; Troch et al., 2013).

Please insert Fig. 13 here

~~*Please insert Fig. 12 here*~~

Please insert Table 6 here

The relationships between the seasonal dryness index and water yield to rainfall ratio (*WY*/*R*) are affected by the duration of the wet season and are depicted in Fig. ~~12~~13. The coefficients of the exponential regression models with their corresponding R^2~~-~~ values pertaining to the wet or dry season are reported for each duration class of the rainy period in Table 6. The exponential curves in the wet season (see plot ~~12a~~13a) are virtually parallel~~ among them~~, yielding, for a fixed ET_p/R, more WY/R as the duration of the rainy period increases from 3-4 months to 7-8 months. In contrast, the exponential regression curves belonging to the dry season (see plot ~~12b) are able to~~13b) explain only a small amount of the variations of WY/R in response to the dryness index and all seem quite insensitive to rainfall seasonality. Only the exponential model pertaining to the dry season and for the smaller duration of the rainy period (3-4 months) explains ~~a bit~~slightly less than 50% of the variability of ET_p/R for the study catchment.

6. Conclusions

Capturing the relationship between ~~rainfall~~ precipitation and catchment-scale water balance components in a Mediterranean context is a scientific challenge in view of ~~climate change in Mediterranean ecosystems. Water yield feeds a multi-use water reservoir~~expected increasing frequencies in ~~the ARC. This study assesses rainfall seasonality by using two different approaches. The first one (static approach) is based on the analysis of the SPI-values by identifying three seasonal features (a 4-month dry season, a 4-month rainy period,~~extremes such as droughts and ~~two 2-month transition seasons). Seasonal anomalies are considered when the transition seasons turn into dry or wet season. The second approach (dynamic approach) is based on the centroid and duration of the rainy period. In this study we assumed the centroid as time-invariant while the temporal variability of the duration is described by a Gaussian~~floods induced by climate warming. On the one hand, intense and prolonged droughts induce a steep decline in water availability for irrigation (with a subsequent decrease in crop productivity), domestic use (especially for the tourist sector), clean power generation, to mention just a few. On the other hand, projected increments in runoff and flooding induce higher-than-normal risk of landslides and soil erosion, compromising the local economy and leading to unprecedented hazards for a vulnerable population. Therefore, countries across the Mediterranean region are being forced to pursue drastic adaptive options which in turn depend on modeling scenarios which can be performed by using hydrological models. Indeed, scenarios need to rely on adequate rainfall modeling within the hydrological year by generating multiple data sets of reliable daily rainfall time series drawn from statistical distributions derived from long-term observations. Nonetheless, a key is first to define rainfall seasons, and then optimize parameters featuring in the best statistical distribution. Rainfall seasonality was decomposed in seasonal duration, mean rainfall depth and describing rainfall frequency. The impact of seasonalitydata distribution in each season. If this exercise is well posed, one can capture realistic rainfall dynamics occurring in the water balance simulated by a numerical model. Within this framework, the aim of this study is to contribute in understanding the impact of rainfall seasonality and its anomalies on the water balance components was evaluated in both approaches by providing simulated water yield, actual evapotranspiration and groundwater recharge within a probabilistic framework. Thereliable and robust scenario-based projections, based on the use of well-posed hydrological models.

This study presented a pilot area (UARC in southern Italy) in the Mediterranean region. We applied the SWAT model that was calibrated and validated in a previous paper using a large amount of environmental data and maps (Nasta et al, 2017). Moreover, the availability of a long-term time series of daily rainfall data (almost one century) allowed us to detect rainfall seasonality by using a static and a dynamic approach. In both approaches we apply the SWAT model to evaluate the sensitivity of hydrological water balance components to rainfall seasonality, using as input synthetic rainfall time series generated by a Poisson process with two parameters that characterize daily rainfall occurrences and daily rainfall depth in each season. In the static approach, dry or wet anomalies are considered when the transition seasons turn into dry or wet seasons. The advantage of this approach lies in its simplicity and easy reproducibility in other sites. However, it can be considered only an artifact based on criteria to group monthly rainfall amounts that might be subjective. In the dynamic approach, the seasonal anomalies occur on the tails of the normal distribution. Both approaches concur on the impact of rainfall seasonal of the wet season duration. Although this approach seems statistically sound, the main disadvantage is the fact that it requires long-term historical rainfall time-series of daily rainfall data that are unlikely to be available in most weather stations across the Mediterranean region. In this study, both approaches concurred on understanding the impact of seasonal rainfall anomalies on catchment-scale water balance components.~~ A~~

Our results show a drought anomaly (i.e. a prolonged duration of the dry season) in just one single year potentially leads to a decrease of even about ~~20% in~~ a fifth of the annual average rainfall ~~inducing~~and induces a drastic decline ~~of about 27%, 10% and 34% of annual~~in average ~~amounts of water yield, actual evapotranspiration and groundwater recharge, respectively. An exceptional prolonged wet season will cause an increase of about 13% in annual average rainfall inducing a rise of about 21%, 3% and 28% of annual average~~ annual amounts of water yield, actual evapotranspiration ~~and groundwater recharge, respectively.~~

, and groundwater recharge. Conversely, an exceptional prolonged wet season is likely to cause a considerable increase in annual average rainfall, hence about a one-third rise in annual average water yield as well as enhanced groundwater recharge. In the dynamic approach, we demonstrated that the implicit assumption of a temporal steady-state in the Budyko relation approach is ~~quite~~ sensitive to rainfall seasonality. The Budyko evaporative index spans from 0.45 to 0.54 when the wet season lasts from 7-8 months up to 3-4 months. Moreover, it is possible to identify distinct ~~seasonal~~season-dependent regression equations linking seasonal water yield to the dryness index over the wet season.

~~A subsequent study will integrate the discussion on water supply with projected water consumption in the next decades induced by socio-economic controls and climate variability. The challenge is to forecast extreme drought episodes in consecutive years that might lead to plausible water crisis at the water reservoir.~~

In conclusion this paper provides a framework to analyze the effects of rainfall seasonality changes on the hydrological water budget and partition, while providing some preliminary results that can be representative for Mediterranean catchments. Finer analyses can be performed by considering consecutive years of prolonged drought episodes and/or by adding the effects of temperature trends, which obviously affect potential evapotranspiration forcing and in principle can produce a further feedback on precipitation cycles. These still unexplored issues will form the subject of future research investigation and forthcoming communications.

7. Appendix

We set k and m as counters for the hydrological year and the 12 months in each year, respectively. The annual rainfall, R_k, and associated monthly probability distribution, $p_{k,m}$, are defined as:

~~The annual rainfall, R_k and associated monthly probability distribution, $p_{k,m}$ are defined as:~~

$$R_k = \sum_{m=1}^{12} r_{k,m} \qquad \text{(A1)}$$

$$p_{k,m} = \frac{r_{k,m}}{R_k} \qquad \text{(A2)}$$

where $r_{k,m}$ represents the rainfall depth recorded in the m-th month in the k-th year.

The relative entropy, D_k, is calculated in each hydrological year, k, as:

$$D_k = \sum_{m=1}^{12} p_{k,m} \, log_2\left(\frac{p_{k,m}}{q_m}\right) \qquad \text{(A3)}$$

where q_m is equal to 1/12 (uniform distribution). This statistical index quantifies the distribution of monthly rainfall within each hydrological year. Finally, the dimensionless seasonality index (DSI_k) in each hydrological year, k, is given by:

$$DSI_k = D_k \frac{R_k}{\bar{R}_{max}} \qquad \text{(A4)}$$

where $\bar{R}_{max}$ is maximum $\bar{R}$. This way DSI_k is zero when rainfall is uniformly distributed throughout the year and reaches its maximum value $log_2 12$ when rainfall is concentrated in a single month.

According to Feng et al. (2013), the magnitude (R_k) represents annual rainfall whereas the centroid (C_k) and the spread (Z_k) indicate timing and duration of the wet season, respectively, and are calculated in each hydrological year k as:

$$C_k = \frac{1}{R_k}\sum_{m=1}^{12} m r_{k,m} \qquad \text{(A5)}$$

$$Z_k = \sqrt{\frac{1}{R_k}\sum_{m=1}^{12}|m - C_k|^2 r_{k,m}} \qquad \text{(A6)}$$

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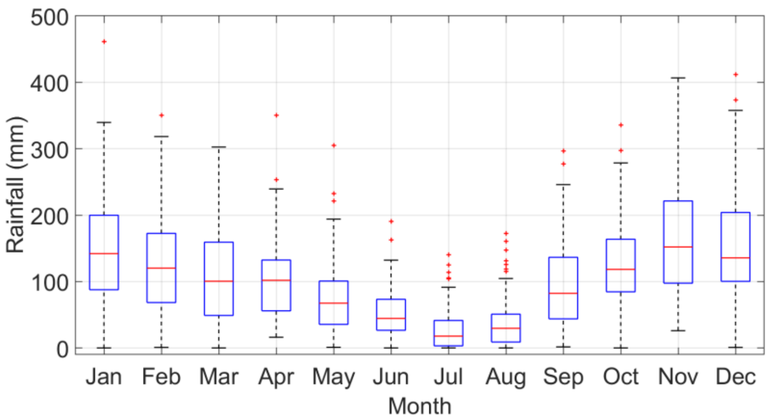
Figures



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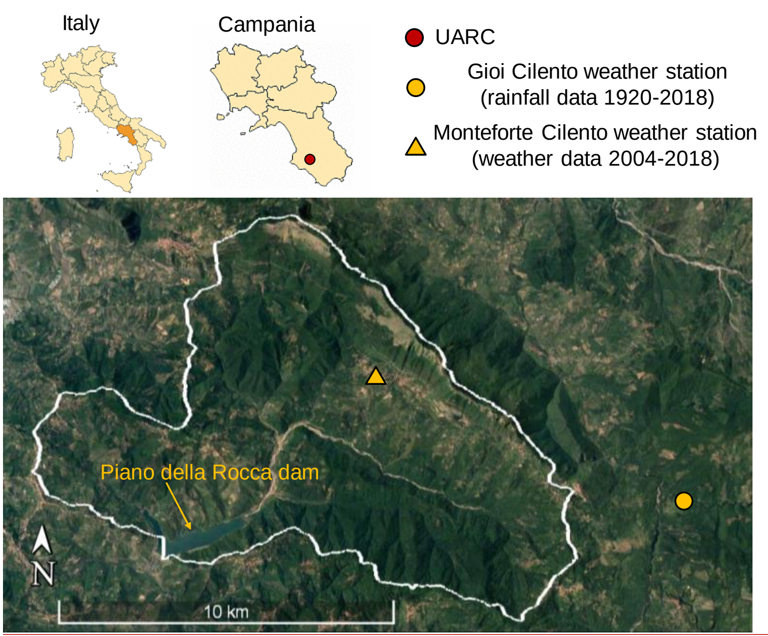

Figure 1: Geographical position of the Upper Alento River Catchment (UARC) in Campania (southern Italy) with the locations of the weather stations of Gioi Cilento and Monteforte Cilento.

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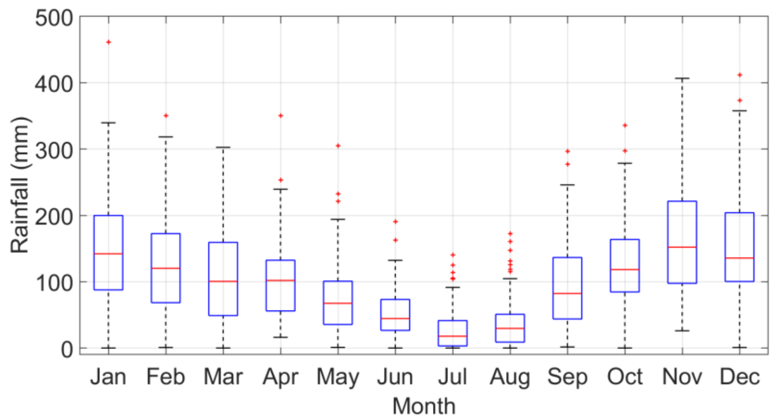

Figure 2: Box plots of the monthly rainfall depths recorded at the Gioi Cilento weather station (1920-2018).

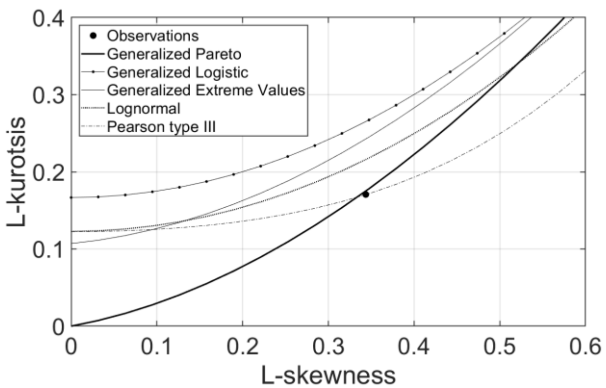

Figure 23: Theoretical L-moment ratio of common distribution models, as compared to the sample L-moment ratios of daily rainfall time series at the Gioi Cilento weather station (large filled large circle).

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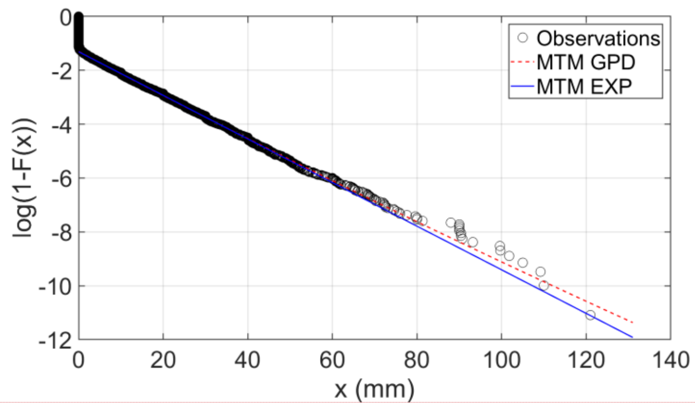

Figure 34: Exponential probability plot of empirical and fitted cumulative distribution functions of daily rainfall depths collected at the Gioi Cilento weather station.

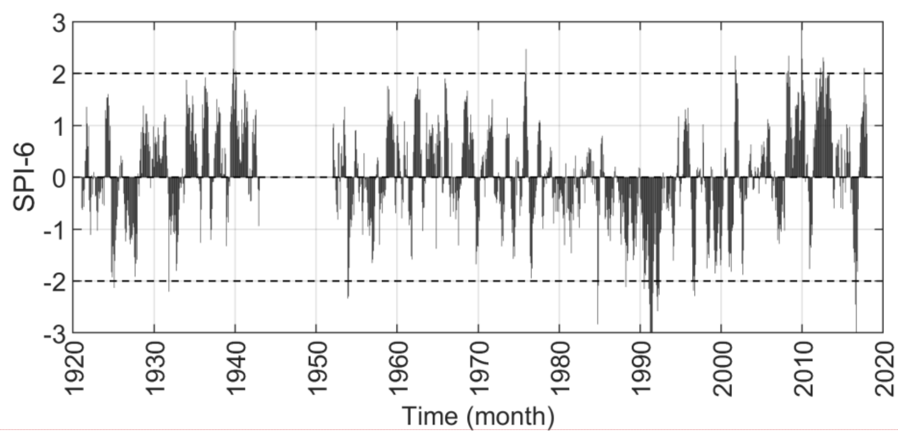

Figure 45: Temporal evolution of SPI-6 spanning from 1920 to 2018 (rainfall data were recorded at the Gioi Cilento weather station).

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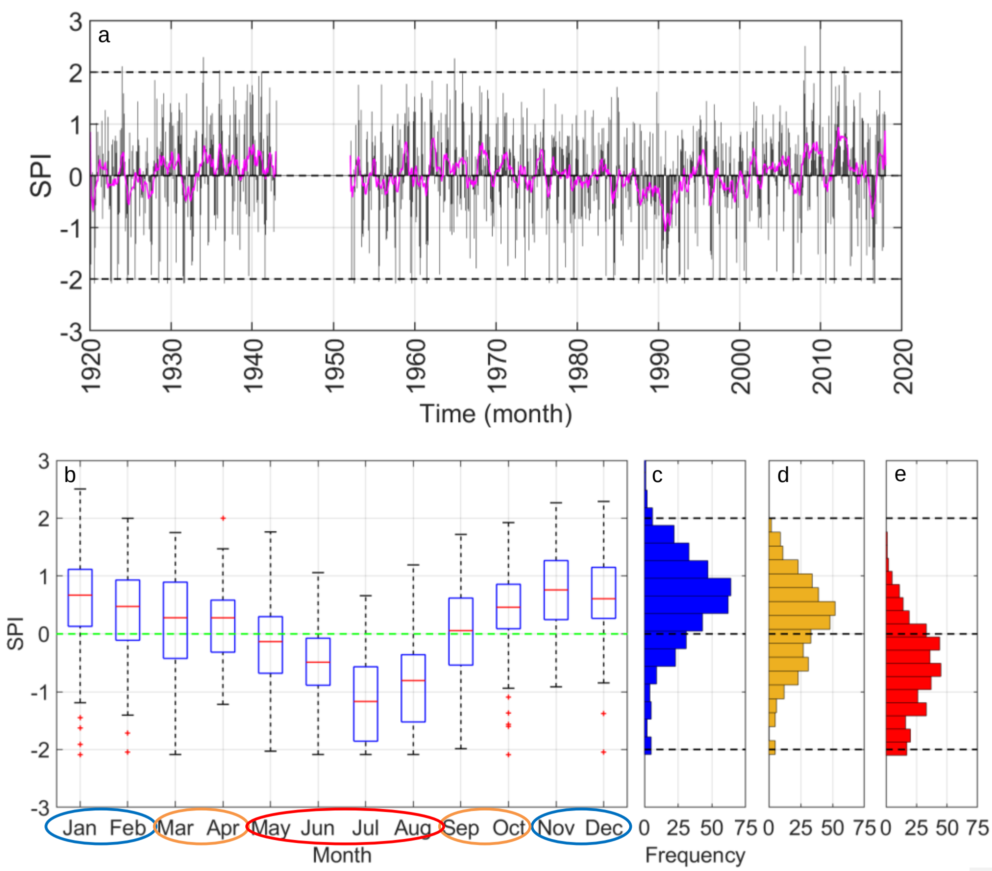

a
SPI
Time (month)
b
SPI
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month
c
d
e
Frequency

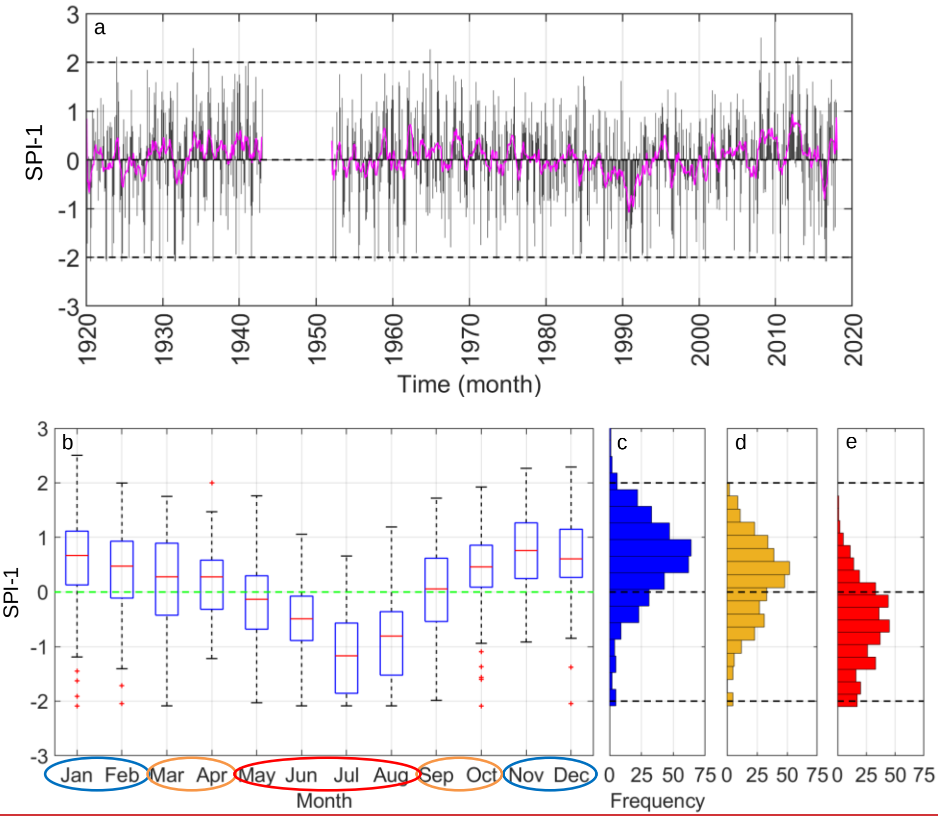

Figure 56: a) Temporal evolution of SPI-1 values (gray bars) and their 12-month moving average (magenta line) spanning from 1920 to 2018 in the static approach; b) Box plots of SPI-1 values and frequency distribution in the c) rainy period (blue histograms corresponding to Nov-Dec-Jan-Feb), d) transition period (yellow histograms corresponding to Mar-Apr-Sep-Oct), e) dry period (red histograms corresponding to May-Jun-Jul-Aug).

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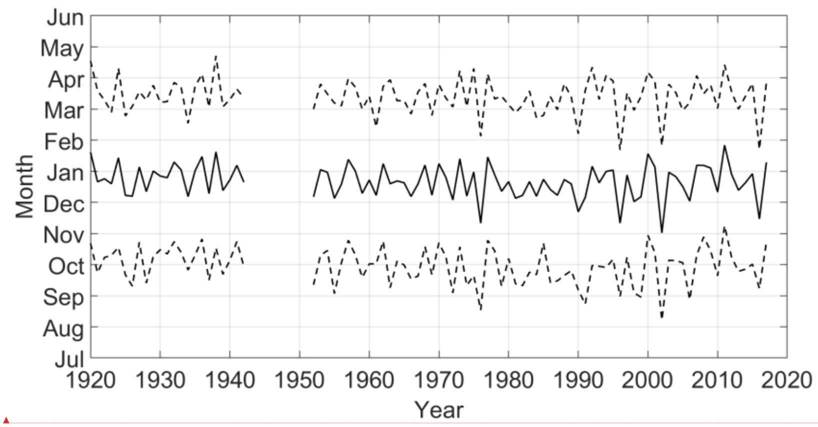

Figure ~~6~~7: Temporal ~~trend~~evolution of the centroid, (or timing (; solid line),) and spread, (or duration (; dashed lines) of the ~~monthly rainfall distribution spanning from 1920 to 2018 in~~wet seasons estimated as proposed by Feng et al. (2013) within the framework of the dynamic approach (rainfall data were recorded at the Gioi Cilento weather station).

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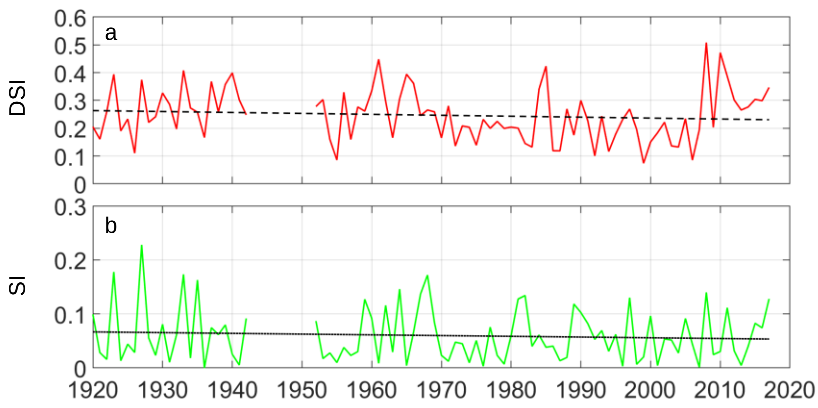

Figure ~~7~~8: Temporal evolution of a) dimensionless seasonal index, DSI (Feng et al., 2013) represented by a red line with corresponding linear regression (dashed line); b) seasonality index, SI (Walsh and Lawler, 1981) represented by a green line with corresponding linear regression (dotted line).

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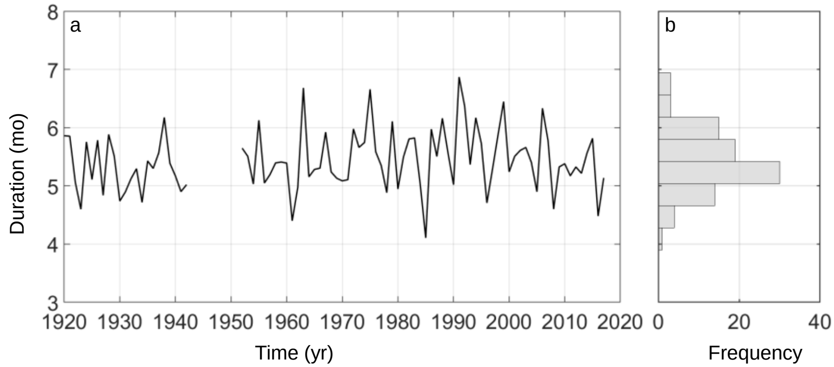

Figure ~~8~~9: Time series (a) and frequency distribution (b) of durations of the rainy periods at the Gioi Cilento weather station in the dynamic approach.

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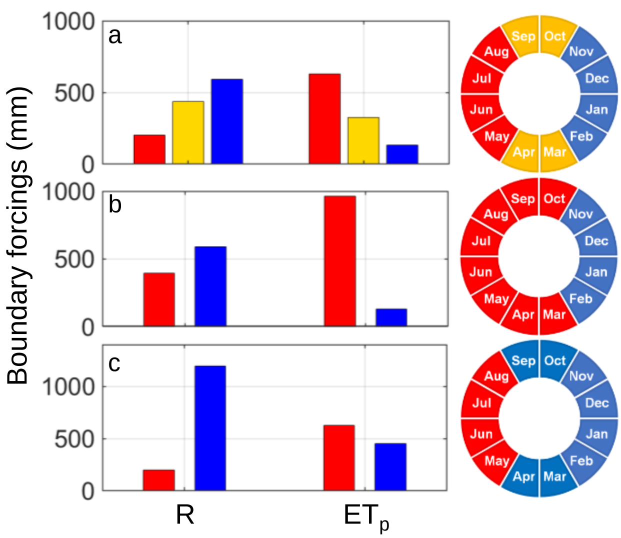
Boundary forcings (mm)
1000
500
0
a
b
c
R
ET$_p$
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug

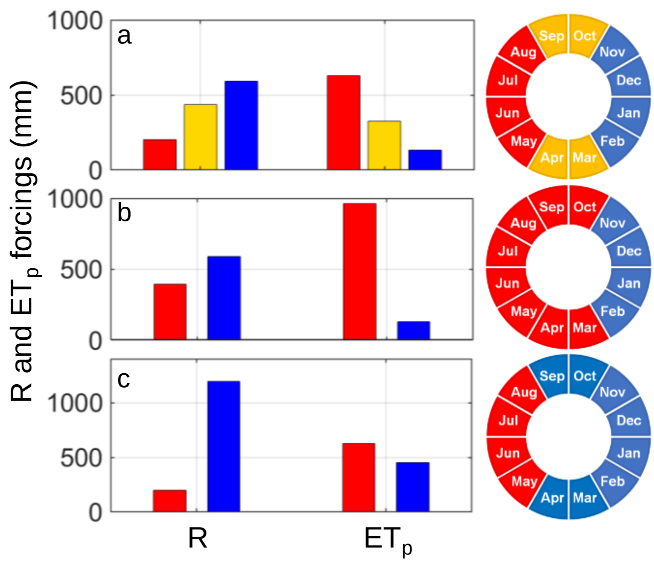

Figure ~~9: Boundary~~10: Rainfall and potential evapotranspiration forcings in the static approach, namely seasonal rainfall (*R*) and potential evapotranspiration (*ET$_p$*) in the dry (red bars), transition (orange bars), and wet season (blue bars). Three scenarios are presented: a) "reference scenario" with the dry, transition, and wet seasons all lasting 4 months; b~~)~~ ") "dry scenario" with the dry and wet seasons lasting 8 and 4 months, respectively; c) "wet scenario" with the dry and wet seasons lasting 4 and 8 months, respectively.

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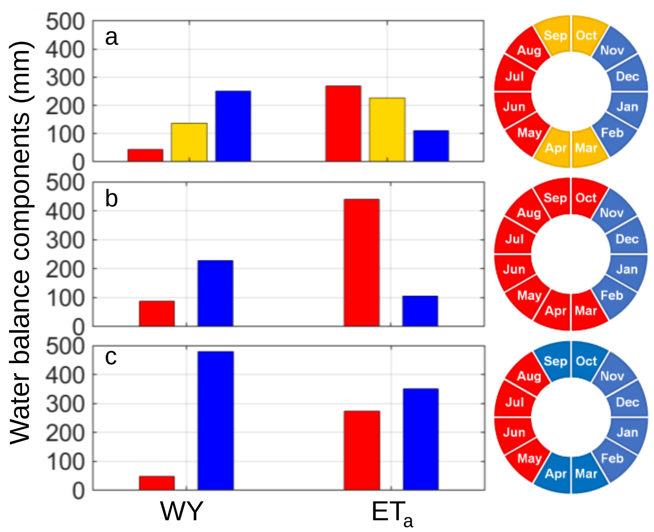

Figure ~~10~~11: Main water balance components in the static approach, namely seasonal water yield (WY) and actual evapotranspiration (ET_a) in the dry (red bars), transition (orange bars), and wet season (blue bars). Three scenarios are presented: a) "reference scenario" with the dry, transition, and wet seasons all lasting 4 months; b) "dry scenario" with the dry and wet seasons lasting 8 and 4 months, respectively; c) "wet scenario" with the dry and wet seasons lasting 4 and 8 months, respectively.

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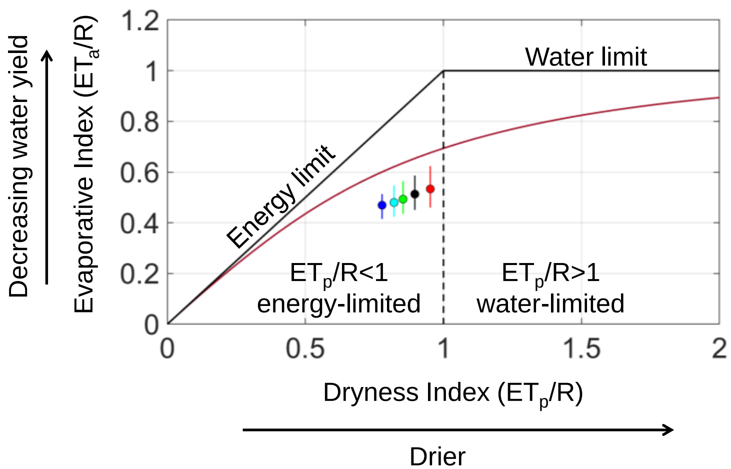

Figure ~~11~~12: Budyko diagram relating the dryness index (*ET_p/R*) with the evaporative (*ET_a/R*) index classified according to the duration of the rainy period pertaining to the dynamic approach. Circles denote median and vertical colored lines represent the range between 5th and 95th percentiles of evaporative index (red, black, green, cyan and blue colors correspond to duration of the rainy period of 3-4, 4-5, 5-6, 6-7 and 7-8 months, respectively). Solid lines denote energy and water limits, the solid garnet line represents the Budyko curve (Budyko, 1974). The vertical dashed line separates left-hand side from right-hand side of the Budyko curve.

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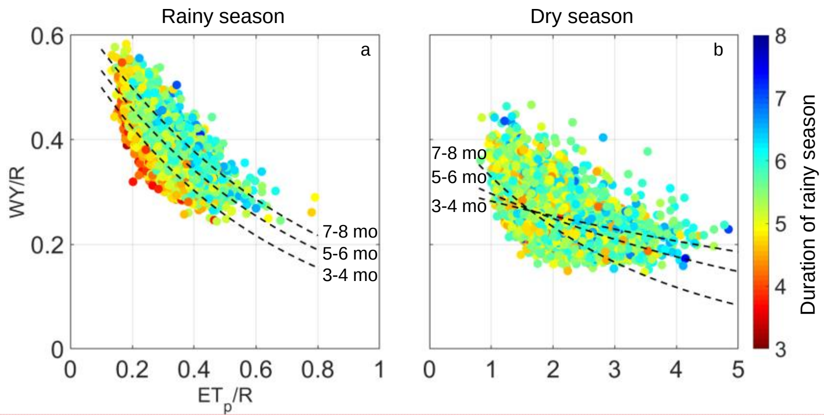

Figure ~~12~~13: Relationship between dryness index and water yield to rainfall ratio (*WY/R*) on a seasonal basis and classified according to the duration of the wet season (from shortest to longest denoted by reddish and bluish colors in the ~~colorbar~~color bar) pertaining to the dynamic approach for the wet season (plot 12a) and the dry season (plot 12b). The exponential regression equations are represented in both plots by the dashed black lines according to the duration of the rainy period.

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Tables

Table 1: Descriptive statistics of the monthly and annual rainfall distributions recorded at the Gioi Cilento weather station during the period 1920-2018.

~~month~~	*mean*	*median*	*min*	*max*	*Std. Dev.*	*CV*
	mm	mm	mm	mm	mm	%
Jan	145.6	141.65	0.0	461.2	81.6	56.0
Feb	128.1	120.25	0.8	350.1	76.3	59.6
Mar	112.9	101.1	0.0	302.6	73.4	65.0
Apr	102.5	101	16.2	350.6	59.5	58.0
May	75.2	67.6	1.1	304.8	56.6	75.2
Jun	52.8	45.3	0.0	190.9	38.2	72.3
Jul	29.8	17.6	0.0	140.4	32.8	110.0
Aug	39.7	30.3	0.0	210	42.8	107.7
Sep	94.4	81.9	1.6	296.8	63.0	66.7
Oct	126.8	118.8	0.0	335.5	70.3	55.4
Nov	166.9	152.2	26.0	613.2	94.9	56.9
Dec	154.6	134.55	0.8	411.8	85.1	55.1
Annual	1229.3	1198.3	478.6	2069.6	295.9	24.1

Table 2: Scenario set-up in the "*static*" approach. Duration and Poisson distribution parameters (η and λ) are reported for each of the considered scenarios.

	Dry season			Transition season			Wet season		
	months	η	λ	months	η	λ	months	η	λ
	-	mm	d^{-1}	-	mm	d^{-1}	-	mm	d^{-1}
Reference scenario (static)	4	8.20	0.196	4	10.53	0.34	4	11.70	0.423
Dry scenario (static)	8	8.20	0.196	0	-	-	4	11.70	0.423
Wet scenario (static)	4	8.20	0.196	0	-	-	8	11.70	0.423

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Table 3: Scenario set up in the "*dynamic*" approach. Duration and Poisson distribution parameters (η and λ) are reported in the dry and wet season.

Dynamic scenario	Dry season			Wet season		
	months	η	λ	months	η	λ
	-	mm	d^{-1}	-	mm	d^{-1}
	random	9.34	0.243	random	11.99	0.413

Table 4: Descriptive statistics of annual water balance components obtained in the three scenarios in the "*static*" approach. Units are mm, except for CV (%).

Scenario	Variable	R	WY	ET_a	GR
		mm	mm	mm	mm
	mean	1229.0	433.3	605.2	194.3
	stand. dev.	176.0	104.2	36.5	48.0
Reference scenario	CV (%)	14.3	24.1	6.0	24.7
	min	586.6	150.8	449.1	44.0
	max	2053.9	1005.9	743.0	389.6
	mean	987.7	317.3	545.1	128.0
	stand. dev.	155.5	88.1	40.8	42.7
Dry scenario	CV (%)	15.7	27.8	7.5	33.4
	min	498.7	96.2	396.0	7.2
	max	1649.9	802.4	691.6	319.3
	mean	1392.8	526.0	625.8	248.1
	stand. dev.	192.4	119.6	34.3	52.6
Wet scenario	CV (%)	13.8	22.7	5.5	21.2
	min	721.9	157.0	481.2	59.0
	max	2179.2	1088.2	748.6	461.6

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Table 5: Water balance components associated to occurrence probabilities for each duration of the rainy period.

	Probability	*R*	*WY*	ET_a	*GR*
	%	mm	mm	mm	mm
3-4 months	0.6%	1,145.0	385.3	608.5	169.6
4-5 months	23%	1,213.4	420.0	619.4	188.0
5-6 months	62%	1,275.4	453.0	624.9	199.6
6-7 months	14%	1,326.0	480.2	631.6	210.2
7-8 months	0.3%	1,383.5	511.6	644.2	211.8

Table 6: Exponential regression models, with the corresponding coefficient of determination (R^2), for the wet and dry seasons as a function of the duration of the rainy period.

Duration	Wet season		Dry season	
	Exp regression function	R^2	Exp regression function	R^2
3-4 months	$WY/R = 0.5914\times\exp(-1.674\times ET_p/R)$	0.440	$WY/R = 0.4635\times \exp(-0.343\ ET_p/R)$	0.482
4-5 months	$WY/R = 0.6031\times\exp(-1.536\times ET_p/R)$	0.579	$WY/R = 0.3675\times\exp(-0.204\times ET_p/R)$	0.290
5-6 months	$WY/R = 0.6171\times\exp(-1.477\times ET_p/R)$	0.587	$WY/R = 0.3530\times\exp(-0.174\times ET_p/R)$	0.279
6-7 months	$WY/R = 0.6313\times\exp(-1.399\times ET_p/R)$	0.617	$WY/R = 0.3476\times\exp(-0.159\times ET_p/R)$	0.284
7-8 months	$WY/R = 0.6586\times\exp(-1.389\times ET_p/R)$	0.585	$WY/R = 0.3137\times\exp(-0.105\times ET_p/R)$	0.211