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# Introducing a modified Reconnaissance Drought Index (RDIe) incorporating effective precipitation

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## Abstract

Drought indices are commonly used tools for drought characterisation and analysis. The Reconnaissance Drought Index (RDI) is one of the widely used indices, due to its high sensitivity and resilience. The basic form of the index is the ratio of the cumulative precipitation to potential evapotranspiration, for a specified reference period. The RDI is also transferred to a normalised and a standardised expression. Since the RDI incorporates both the main input and the main output of a natural water system, it is considered as an appropriate index of water availability. Based on this notion, as shown in recent studies, the RDI is suitable for the assessment of drought impacts on agriculture. In this paper, a modified version of the index, RDIe, is presented, in which precipitation is replaced by the effective precipitation. With the proposed modification, the amount of water beneficially exploited by the agricultural systems can be represented more accurately, enhancing the performance of the index for agricultural drought analysis. Further, alternative ways for the calculation of effective precipitation are presented and discussed. An application of the modified RDI in an agricultural area demonstrates its better performance in assessing the impacts of drought on the rainfed agricultural production.

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*Keywords:* meteorological drought; agricultural drought; drought indices; Reconnaissance Drought Index

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## 1. Introduction

Drought is a natural phenomenon with significant effects on several sectors (economy, society, environment). Conventionally, based on the sector or water-system of interest, the drought phenomenon is characterised as meteorological, hydrological and agricultural [1]. The selection of the appropriate variables for drought analysis mainly depends on the water system under study [2].

Drought characterisation and analysis are crucial aspects for drought management and operational planning. The quantification of drought severity, which is usually achieved through the use of drought indices, is the main element of drought analysis. Many drought indices have been developed in the past, for general or specific use, serving different research or operational objectives [3-5].

The precipitation is the principal parameter for many drought indices. However, based on recent reports by the Intergovernmental Panel on Climate Change [6,7], the observed climate variability for various meteorological parameters (e.g. precipitation, temperature) follows different patterns in several regions of the world. Additionally, the regional characteristics of droughts are expected to change, as a result of the variation of meteorological parameters or due to the cumulative adverse effect of more than one parameter (e.g. decrease of precipitation and increase of temperature) [8]. Therefore, indices that incorporate temperature in their formulation are considered more appropriate for representing the climate change conditions [9-12].

In this paper, a modified version of the Reconnaissance Drought Index (RDI), which incorporates both precipitation and temperature (through the use of potential evapotranspiration), is proposed. The RDI is characterised mainly as a meteorological index, though, due to its structure, has been proved appropriate for the assessment of agricultural droughts [13,14]. However, the total precipitation cannot usually represent sufficiently the amount of water that can be used consumptively by the plants. For this reason, the use of the effective precipitation, instead of total precipitation, is proposed for RDI modification. This approach is expected to increase the suitability of the index for the assessment of drought effects on the agricultural systems, especially for rainfed conditions.

## 2. Methodological approach

### 2.1. Effective precipitation

The concept of the effective precipitation ($P_e$) may have different interpretation for each scientific field or for different research objectives. For instance, $P_e$ could be considered, respectively, as the total amount of the precipitation that enters into a reservoir, the percentage of the precipitation that contributes to groundwater recharge, the amount of water that can be used by the root system of the plants, etc. In this paper, we focus on the concept of $P_e$ as a factor that contributes to agricultural production. Therefore, $P_e$ is considered as the part of total precipitation that can be used for crop development, directly or indirectly.

The soil water conservation in the root zone can be expressed through the following equation [15]:

$$\Delta V = P + IR - (I + Q + ET + DP) \tag{1}$$

in which $\Delta V$ is the change of soil water in the root zone, $P$ is the precipitation, $IR$ is the irrigation water depth, $I$ represents the interception losses, $Q$ is the runoff, $ET$ is the evapotranspiration and $DP$ is the deep percolation. All units are expressed in mm and refer to a time period of $\Delta t$.

The $P_e$ is defined as the percentage of the total precipitation that enters into the soil (root zone), but it is not lost due to deep percolation:

$$P_e = P - (I + Q + DP) \tag{2}$$

The percentage of total $P$ that is considered as $P_e$ depends on several factors, which may also have a combined effect. Practically, any factor that is related to infiltration, runoff and evapotranspiration is influencing the value of $P_e$ [16,17].

The $P_e$ can be measured through several techniques, e.g. soil moisture change, lysimeters, etc., however, these techniques are mainly limited for experimental applications. In some regions, there are studies for the development of equations that determine $P_e$, based on the local conditions and characteristics (topography, main soil types, etc.). These approaches usually give good practical results, though their application is limited to the specific regions for which they were developed.

Other empirical methods have been also used, that provide a generic assessment of $P_e$. The simplest approach is to calculate $P_e$ as a specified percentage (usually 70-90%) of the total precipitation. Based on this, other criteria may be also used for a more precise estimation. For instance, Caruso et al. [18] estimated $P_e$ as the 75% of total daily precipitation, neglecting the days with precipitation depth lower that 4 mm.

The U.S. Bureau of Reclamation has also developed a method for $P_e$ estimation, which is mainly proposed for arid or semi-arid regions. In this method, classes of the total monthly precipitation are used (Table 1), in order to define the corresponding percentage for the calculation of $P_e$ [19]. Alternatively, the following equation may be used [20]:

$$\left\{\begin{matrix} P_e = P \cdot (125 - 0.2 \cdot P)/125 & \text{for } P \leq 250 \text{ mm} \\ P_e = 0.1 \cdot P + 125 & \text{for } P > 250 \text{ mm} \end{matrix}\right\} \tag{3}$$

Table 1. Estimation of effective precipitation based on total monthly precipitation classes (U.S. Bureau of Reclamation method).

| Total monthly precipitation class (mm) | Effective precipitation class (%) |
|---|---|
| 0.0 - 25.4 | 90 - 100 |
| 25.4 - 50.8 | 85 - 95 |
| 50.8 - 76.2 | 75 - 90 |
| 76.2 - 101.6 | 50 - 80 |
| 101.6 - 127.0 | 30 - 60 |
| 127.0 - 152.4 | 10 - 40 |
| > 152.4 | 0 - 10 |

A more thorough estimation method has been proposed by U.S.D.A. [21], which was developed based on the analysis of 50-years of data from 22 areas with different climatic and soil conditions. The assessment of monthly $P_e$ is based on total precipitation ($P$), crop evapotranspiration ($ET_c$) and a soil water storage factor ($SF$), according to the following equation (in which the parameters are expressed in mm) [17,22]:

$$P_e = 25.4 \cdot SF \cdot (0.04931 \cdot P^{0.82416} - 0.11565) \cdot 10^{0.000955 \cdot ET_c} \tag{4}$$

in which $SF$ is defined as:

$$SF = 0.531747 + 0.011621 \cdot D - 8.943 \cdot 10^{-5} \cdot D^2 + 2.321 \cdot 10^{-7} \cdot D^3 \tag{5}$$

in which $D$ is the usable soil water storage and is approximately between 40 to 60% of the available soil moisture in the root zone. It is noted that $P_e$ cannot be greater than the monthly precipitation or the monthly evapotranspiration. If the result is greater than any of these parameters, the $P_e$ is considered equal to the lower of the above values.

Another empirical method has been proposed by FAO [23]. According to this method, the following equation may be used for the estimation of $P_e$, based on the corresponding value of the total monthly precipitation:

$$\left\{\begin{matrix} P_e = 0 & for\ P \leq 12.5mm \\ P_e = 0.6 \cdot P - 10 & for\ 12.5mm < P \leq 70mm \\ P_e = 0.8 \cdot P - 25 & for\ P > 70mm \end{matrix}\right\} \tag{6}$$

### 2.2. Modified Reconnaissance Drought Index

The Reconnaissance Drought Index (RDI) has been introduced by Tsakiris and Vangelis [24] as a physically based, universal and comprehensive index for the assessment of meteorological drought. It utilises two parameters, the cumulative precipitation (*P*) and potential evapotranspiration (*PET*), for specified reference periods. Recent studies [25,26] have shown that temperature methods for estimating *PET* can be sufficient for the calculation of RDI in various regions, therefore the data requirements are limited to precipitation and temperature. Over the last decade, the RDI has been widely used in several applications worldwide [e.g. 27-31].

The RDI can be expressed in three forms. The initial form of the index ($\alpha$) within a year for a reference period of k months is calculated as [32]:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \tag{7}$$

The second form is a normalised expression of the index ($RDI_n$), calculated by the following equation:

$$RDI_n(k) = \frac{a_k}{\bar{a}_k} \tag{8}$$

in which $\bar{a}_k$ is the long term average of $\alpha_k$.

Assuming that the values of $\alpha_k$ follow the log-normal distribution, the standardised form of the index ($RDI_{st}$) is calculated as [24]:

$$RDI_{st}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k} \tag{9}$$

in which $y_k$ is equal to the $\ln\alpha_k$, while $\bar{y}_k$ is its average and $\hat{\sigma}_k$ is its standard deviation, respectively.

The above approach for the calculation of $RDI_{st}$ cannot be used in case of zero precipitation sums. For this reason, alternative techniques have been proposed [33,34]. Drought characterisation can be performed based on drought severity classes [35].

Previous studies have shown that RDI can be successfully used for the assessment of drought effects on crop yield, especially in rainfed agriculture [13,14]. However, as already mentioned, the $P_e$ is expected to better represent the amount of water that is used beneficially by the crops. Therefore, a modified version of RDI, RDIe, is proposed in this paper, by replacing the total precipitation by the $P_e$. Based on Equation (7), the modified initial form of the index ($\alpha_e$) is calculated as:

$$a_{ek} = \frac{\sum_{j=1}^{j=k} P_{ej}}{\sum_{j=1}^{j=k} PET_j} \tag{10}$$

The calculation of the normalised ($RDIe_n$) and the standardised ($RDIe_{st}$) forms of the index can be performed with similar procedures, as already described for RDI.

The $P_e$ can be estimated with the previously mentioned methods, depending on the conditions of each study area. Obviously, for consistency reasons, the same $P_e$ estimation method should be used in case of spatial drought analysis.

### 2.3. Calculation of the modified RDI using the DrinC software

As known, the Drought Indices Calculator (DrinC) software has been developed aiming at providing the means for the consistent calculation of various drought indices for drought analysis in research and operational applications [36,37]. A special routine has been added to DrinC software that can be used for the calculation of the modified RDI

(RDIe). The estimation of $P_e$ through this routine can be performed with the above described methods of the U.S. Bureau of Reclamation [19,20] and FAO [23].

## 3. Application

For illustration purposes, the proposed RDIe is used in Larissa valley, an area with major agricultural activity in central Greece. Meteorological data (precipitation, minimum and maximum temperature) of the Hellenic Meteorological Organisation for 47 hydrological years (1955-2002) are used. The *PET* is estimated with Hargreaves method [38]. The climate of the study area is characterised as semi-arid, therefore the U.S. Bureau of Reclamation method is considered appropriate for the calculation of $P_e$.

In Figure 1, the values of the original and modified $\mathrm{RDI_{st}}$ are presented, for three reference periods. The first period (October – September) represents the entire hydrological year, the second (October – June) the first nine months of the hydrological year, while the third period (November – May) corresponds to the development stages of winter wheat, which is the main rainfed crop in the area. It is observed that the values obtained by the initial and the modified forms of RDI exhibit differences, which, in some cases, may lead to different drought characterisation.

The approach proposed by Tigkas and Tsakiris [14] is used to test the response of the original and modified RDI in order to assess the drought effects on wheat yield for the specific area. This approach employs AquaCrop model [39] for the simulation of wheat yield, while regression models are used for the correlation between RDI and crop yield. Here, for simplicity purposes, only the correlation coefficient (*r*) for the three reference periods is used, as a simple indicator of the performance of RDI and RDIe (Table 2).

Table 2. Correlation coefficient between winter wheat yield and the original and modified versions of RDI (RDI and RDIe) for three reference periods in the area of Larissa (1955 – 2002).

| Reference period | Correlation coefficient (*r*) | |
|---|---|---|
| | $\mathrm{RDI_{st}}$ | $\mathrm{RDIe_{st}}$ |
| 12-month (October-September) | 0.678 | 0.688 |
| 9-month (October-June) | 0.655 | 0.692 |
| 7-month (November-May) | 0.775 | 0.795 |

The above presented results give the indication that RDIe has better performance for the three tested periods. It should be also noted that the 7-month period, which corresponds to the crop development period, presents higher correlation coefficient compared to the other periods. This can be a critical point for the association of the effects of drought with crop yield.

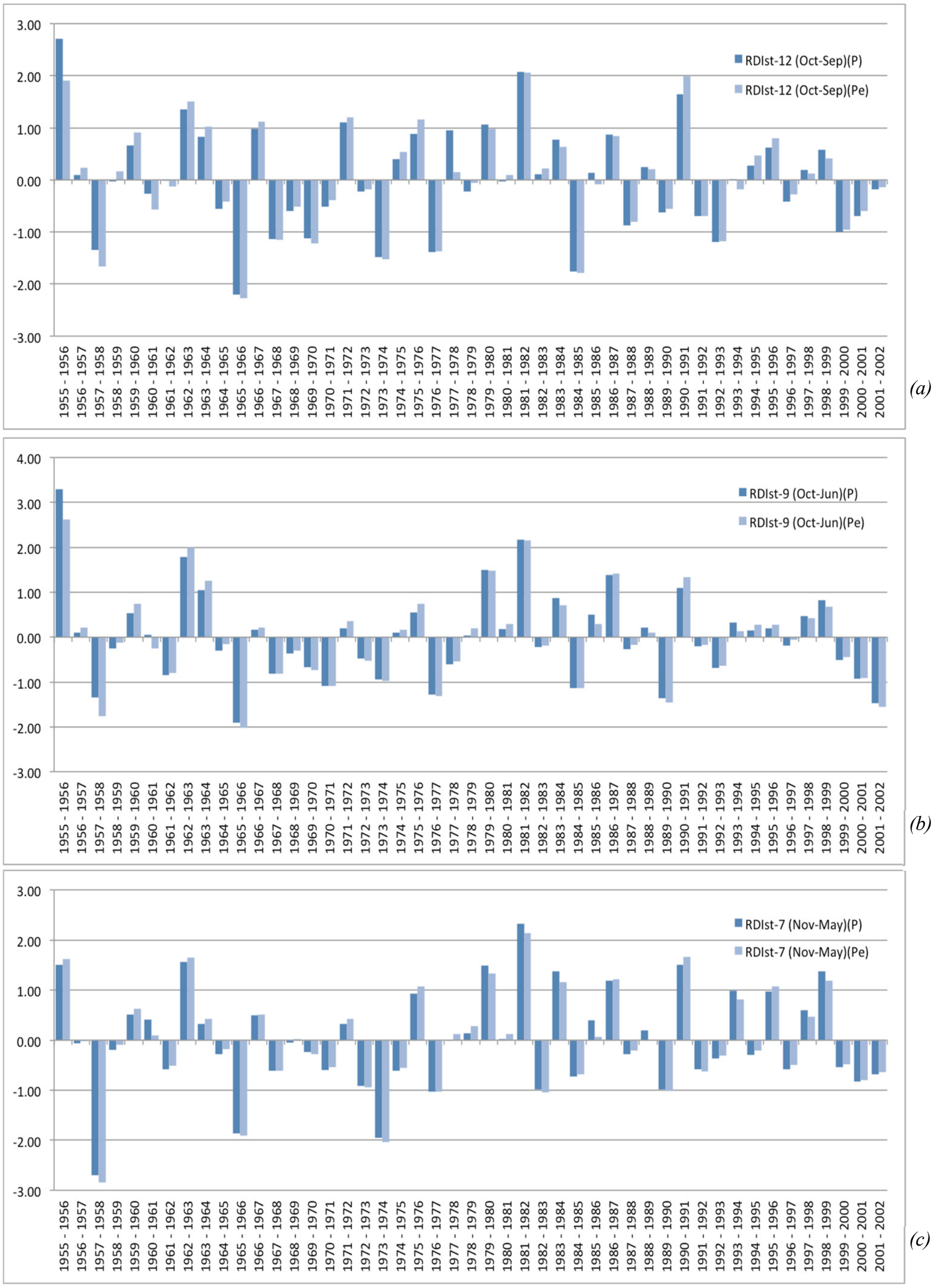

Fig. 1. Values of the original and modified $RDI_{st}$ for the area of Larissa for 3 reference periods: a) $RDI_{st}$-12 (October-September), b) $RDI_{st}$-9 (October-June) and c) $RDI_{st}$-7 (November-May).

## 4. Concluding remarks

The RDI is a widely used index, which has been successfully employed in numerous drought-related studies during the last decade. In this paper, a modified version of the index, RDIe, is introduced, by replacing precipitation by effective precipitation. Compared to the total precipitation, the effective precipitation expresses more accurately the amount of water that can be productively used by the crops. Therefore, the RDIe is expected to enhance the link between drought severity and the reduction of the agricultural production.

The use of the RDIe is illustrated through an application in an agricultural area in Greece. The results showed that the modified index is better correlated to the crop yield reduction of the winter wheat, indicating that the proposed index may be a useful tool for characterising agricultural drought and for the assessment of impacts on rainfed crop yield.

More comprehensive applications of the RDIe, in regions with different climatic conditions and other crops, are expected to give better insights on the validity of the proposed modified index.

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