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Variability and Change in Water Cycle at the Catchment Level

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Abstract

This study proposes a simple methodology for assessing future-projected evolution of water cycle components (precipitation, potential evapotranspiration, and potential runoff) based on the two-level Palmer model of the soil and their impact on drought conditions at basin level. The Palmer Drought Severity Index (PDSI) is used as drought metric. The catchments of rivers Arges, Mures, Prut, Siret and Someș (mid- and lower Danube basin) have been chosen as case studies. The present climate data consist of Romanian gridded dataset, monthly precipitation and values of streamflow from Romania and Republic of Moldova and potential evapotranspiration-related data from the Climate Research Unit (University of East Anglia). We used as future projections five numerical experiments with regional models obtained through the EURO-CORDEX initiative, under two Representative Concentration Pathway scenarios. The correlations between observed streamflow at the river basin outlets and PDSI-related components of the water cycle show that PDSI represents reasonably well processes taking place in the selected catchments. Depending on the specific scenario and catchment, droughts that in the Palmer classification were deemed as incipient, mild or severe under present climate will become a normal summer feature toward the end of this century, especially over catchments situated in the lower Danube basin.

Keywords: climate change, Palmer Drought Severity Index, regional climate modeling, EURO-CORDEX, mid and lower Danube basin

1. Introduction

The Fifth Assessment Reports of the Intergovernmental Panel on Climate Change [1] indicates that climate change is unequivocal, and this fact is clear from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and the rising global sea level. Global warming leads to warmer lower atmosphere and increased evaporation rates, resulting in an enhancement in the amount of moisture transport in the troposphere. An observed effect of higher water vapor concentrations is the increased frequency of extreme precipitation events over land areas. Warmer temperatures have led to increased drying of the land surface in some areas, with the effect of an increased incidence and severity of drought. Climate change is affecting the water cycle, enhancing droughts in some areas and wet conditions in others [1]. In parts of the Northern Hemisphere, spring conditions have the tendency to develop earlier, leading to a shift in peaks in snowmelt and river streamflow. As a consequence, summers tend to experience reduced water availability. Furthermore, these changes are likely to intensify in future under higher greenhouse gas (GHG) global concentrations.

Even though the broad picture of climate-induced changes in water cycle is relatively clear, there are regional details that locally impact the water cycle, and this is the level where the adaptation measures have to be implemented for a sustainable development of the society. Climate impact assessments and local adaptation strategies require analysis based on numerical experiments using climate models with very high spatial resolution under scenarios of global climate change and robust evaluation of the results within the limits of reasonable uncertainty. However, few studies have documented water cycle-related changes at the river basin level based on the new regional climate modeling results in South Eastern Europe. A detailed analysis of future climate change projections exists for the Bârlad basin [2], considering the scenarios elaborated within the Fifth Report of the Intergovernmental Panel on Climate Change [1]. The results presented in [2] show that, under the climate change, the tendency toward more severe summer droughts is a significant feature of the Bârlad basin in the long run, despite the uncertainties related to global and regional models, parametrization of potential evapotranspiration in the Palmer model, and the soil data. This tendency seems to be a result of a basin-wide decrease in the precipitation and increase in the potential evaporation, which have been also identified as causes for the summer time drying in mid-latitudes in the CMIP 3 model results [3]. However, it is still an open question if these results apply for other river catchments, too.

The main objective of this study is to propose a robust methodology for assessing the present and future-projected evolution of local water cycle components and their impacts on drought conditions at the basin level in mid-latitude areas, using results of regional climate experiments under the representative concentration pathway (RCP) scenarios [4]. The catchments selected as case studies are located in the mid- and low-Danube basin (**Figure 1**).

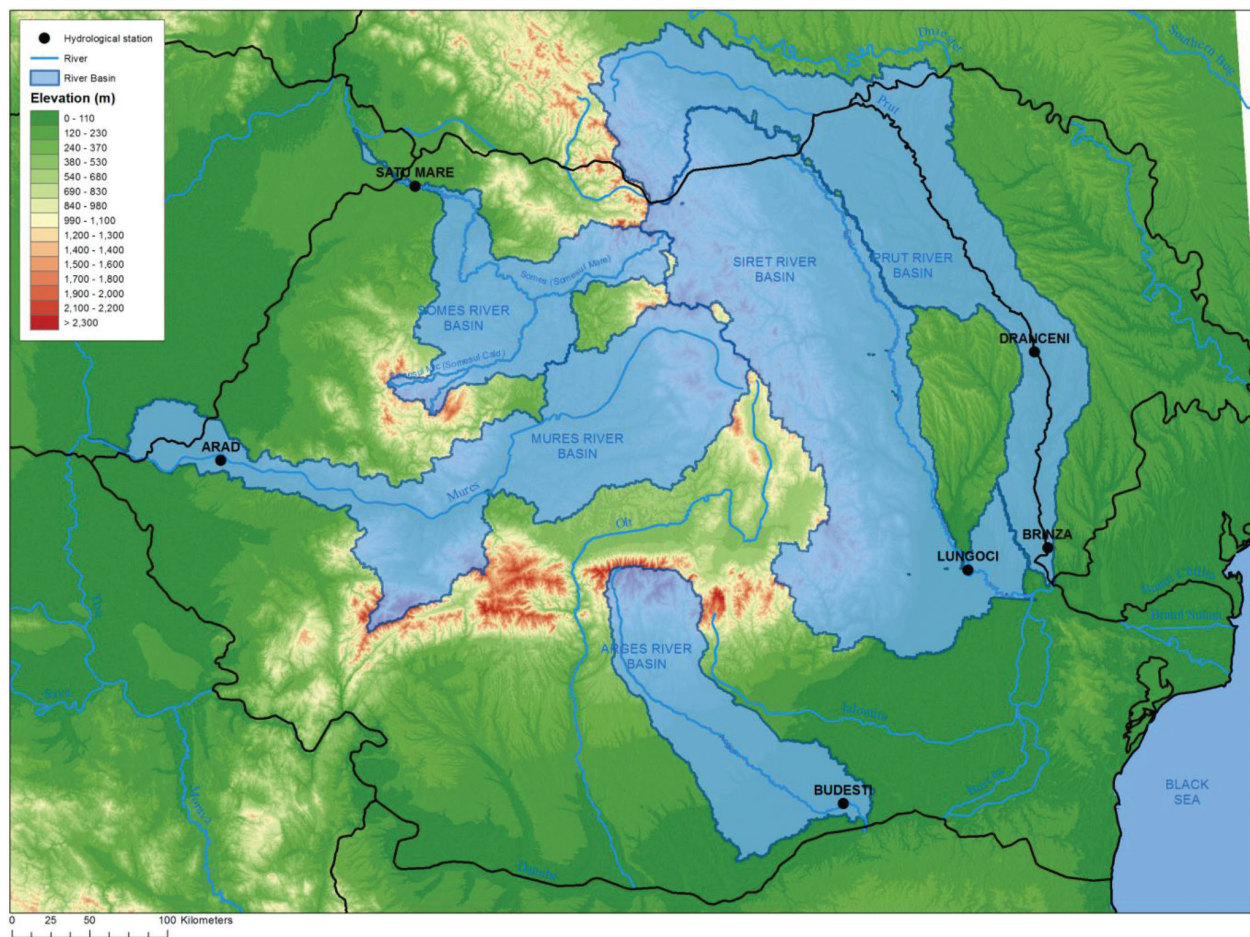


Figure 1. Location of the selected catchments (light blue area, dark blue edges). Shaded colors illustrate the topography. Blue lines represent the rivers. Hydrometric stations for each selected catchment are represented by black circles.

In this area, usually, snow melting and rain provide the main supply for surface waters [5]; thus, they are relevant for climate-induced changes in water cycle at catchments level, in mid-latitudes.

2. Data

We extracted daily and monthly data from observations and model results covering the selected river basins. The time slices of simulated and observed available data are included in the interval 1951–2015. The future projections used here are computed under the representative concentration pathway (RCP) scenarios. The RCP scenarios describe the temporal evolution of the global greenhouse gas concentrations in the period 2006–2100. They illustrate the radiative forcing due to increased concentration of greenhouse gases. In 2100, the radiative forcing caused by increased levels of greenhouse gases reaches a value around 4.5 (8.5) W/m² above the pre-industrial level in the RCP 4.5 (RCP 8.5) scenario [4].

The CMIP5 results have a global coverage with a spatial resolution suitable for large-scale analysis. However, this resolution is not quite appropriate for a detailed description of local

No.	Regional climatic modeling center	Regional climate model (RCM)	Global climate model (GCM)
1	DMI (Danish Meteorological Institute)	HIRHAM5	ICHEC-EC-EARTH
2	KNMI (Royal Netherlands Meteorological Institute)	RACMO22E	ICHEC-EC-EARTH
3	SMHI (Swedish Meteorological and Hydrological Institute)	RCA4	ICHEC-EC-EARTH
4	SMHI (Swedish Meteorological and Hydrological Institute)	RCA4	MPI-ESM-LR
5	SMHI (Swedish Meteorological and Hydrological Institute)	RCA4	IPSL-CM5A-MR

Table 1. Numerical experiments with regional and global climate models used to assess the influence of climate change on the future evolution of water cycle components in the selected basins.

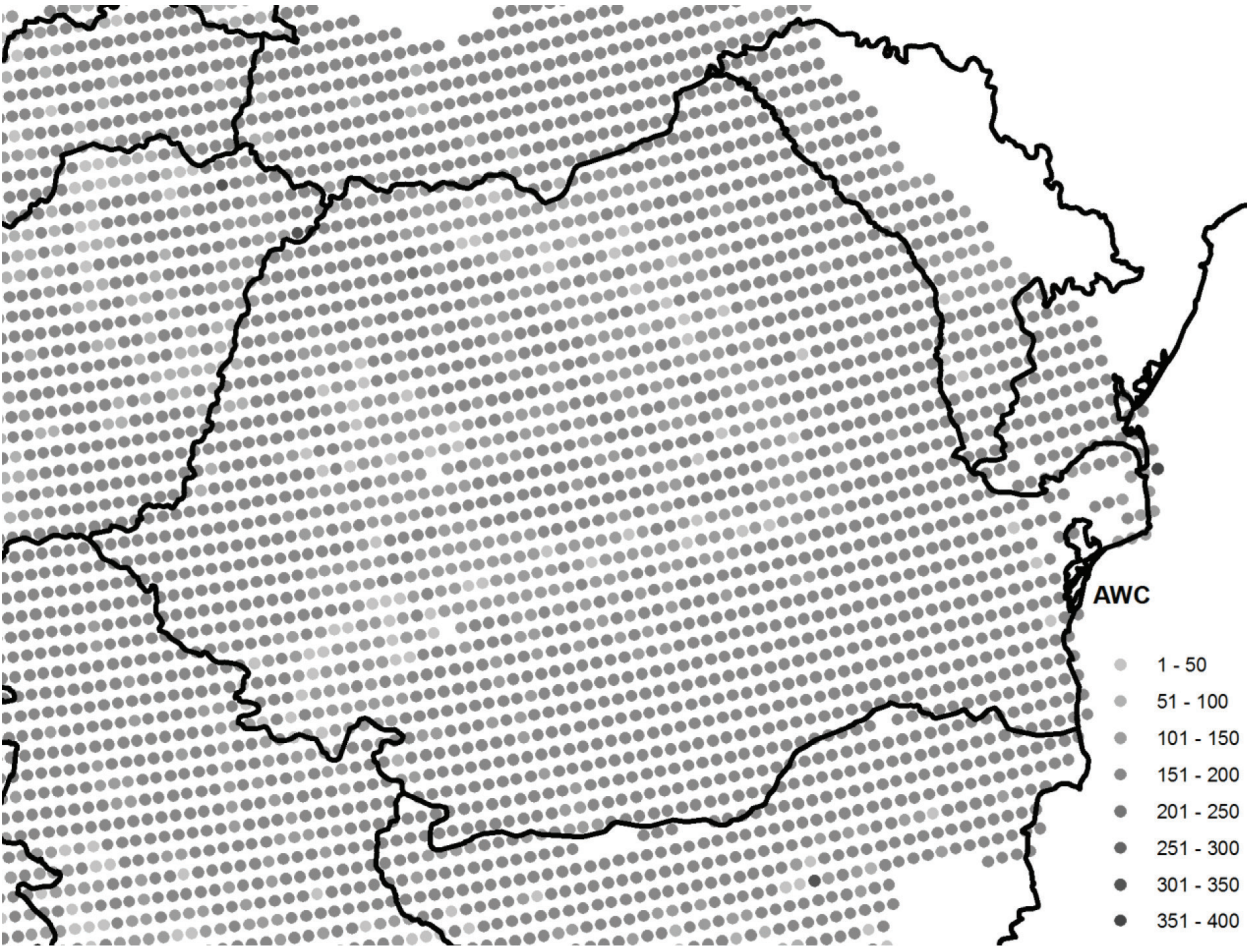


Figure 2. Available water capacities (AWCs) (in mm water column/1 m soil) computed in the 12.5 km EURO-CORDEX grids (black circles) obtained as the sum of topsoil and subsoil AWCs (at 1 km × 1 km resolution) extracted from the European Soil Database (ESDB) and averaged over the 12.5 km × 12.5 km grid cells centered in the model grids for the areas of interest.

processes like those taking place in river catchments. That is why we used regional climate models from COordinated Regional Climate Downscaling Experiment (CORDEX) [6] driven by global models from the CMIP5. As part of CORDEX framework, EURO-CORDEX initiative

provides regional climate projections for Europe at resolutions of 50 km (EUR-44) and 12.5 km (EUR-11). In this study, we use the available EURO-CORDEX results with very high resolution (EUR-11). The regional and global climate models used for numerical experiments analyzed in this study are presented in **Table 1**.

We used observation-derived gridded data in comparison with model results to see how the regional climate models simulate the present climate. Observed data were extracted from the ROCADA data set for the period 1970–2005. The ROCADA data set contains daily values and has a spatial resolution of 10 km × 10 km [7, 8]. We have also extracted gridded temperature, precipitation and potential evapotranspiration (resolution 0.5° × 0.5°) from the global data set developed at Climate Research Unit (CRU) [9]. The CRU potential evapotranspiration follows the Penman-Monteith approach [10]. A gridded precipitation data covering the entire transboundary basin of Prut river at the spatial resolution of 10 km × 10 km was built in the framework of IMDROFLOOD project, using observations from Romania, Republic of Moldova and data extracted from the Global Historical Climatology Network-Daily (GHCND-D) [11]. Monthly values of streamflow at stations from Romania and Republic and Moldova were also used in the case of the Prut transboundary basin.

In addition, we used available water capacities (AWCs) of soils. The AWC dataset consists of estimated topsoil and subsoil AWC values extracted from the European Soil Database (ESDB) [12, 13] for the studied areas.

In this study, we averaged the sum of topsoil and subsoil AWCs from the ESDB on the 12.5 km × 12.5 km (50 km × 50 km) square cells centered in the climate model (CRU data) grids to provide the soil constants used as input data for PDSI calculation in each EURO-CORDEX (CRU) grid point of the selected basins. For example, the AWC data averaged at the EURO-CORDEX resolution are illustrated in **Figure 2**.

3. Methodology

In our approach, we define the local water cycle components (precipitation, potential evapotranspiration, and potential runoff) based on the two-level model of the soil exploit by the Palmer Drought Severity Index (PDSI) [14], like in the approach presented in [2]. The top layer of soil is assumed to hold 25.4 mm of moisture. The amount of moisture that can be held by the two-layered soil is a soil-dependent value—available water capacity (AWC)—which must be provided as an input parameter [14].

The PDSI measures the cumulative effect of monthly precipitation deficit/surplus with respect to a value that is climatologically appropriate for existing conditions (CAFECS) in a given region [14]. The computation of the PDSI requires precipitation, air temperature, soil characteristics (i.e., available water capacity—AWC), and the latitude of the location to estimate the length of day over which the solar radiation is received (for deriving potential evapotranspiration). In order to calculate the PDSI for a certain month (i), one has first to determine the moisture anomaly index ZINDi for that month (i):

$$\text{ZIND}_i = k (P - \alpha \text{PE} - \beta \text{PR} - \gamma \text{PRO} + \delta \text{PL}) \quad (1)$$

$$PDSI_i = PDSI_{i-1} + ZIND_i/3 - 0.103 PDSI_{i-1} \quad (2)$$

where k is an empirical weighting factor, specific for each region; α , β , γ , and δ are coefficients for evapotranspiration, soil water recharge, runoff and water loss from the soil, computed to link the potential quantities and real ones; and P , PET , PR , PRO , and PL represent the observed precipitation, Thornthwaite potential evapotranspiration [15], potential recharge, potential runoff and potential water loss from the soil. Potential evapotranspiration (PET) is the maximum evapotranspiration in the given environmental conditions, when soil moisture is not a limiting factor. Potential recharge (PR) is the amount of moisture required to bring the soil to its AWC from the available moisture at the beginning of the month. Potential run-off (PRO) is defined as the difference between the potential precipitation and the potential recharge. Runoff is assumed to occur if the Palmer soil model reaches its available moisture capacity, AWC. Potential loss (PL) is the amount of moisture that could be lost from the soil provided that the monthly precipitation is zero [14].

Palmer [14] built the index based on the simple representation of the components shaping the hydrological balance in a given area from the United States of America. We used the self-calibrated version of the PDSI [16] that automatically calibrates the behavior of the index at any location by replacing empirical constants in the index computation with dynamically calculated values.

The water balance model proposed by Palmer uses the Thornthwaite parametrization for potential evapotranspiration [15], which is solely based on the air temperature, and the solar radiation contribution is empirically derived under the current climate conditions. Under the climate change, the Thornthwaite empirical approach seems to overestimate the upward trends in potential evapotranspiration [4, 17, 18]. The Penman-Monteith method uses a more physically oriented parametrization to estimate the potential evapotranspiration explicitly based on temperature, net radiation, air pressure, air humidity and wind data [10]. Thus, we have extracted and/or computed the Penman-Monteith version of potential evapotranspiration from the EURO-CORDEX archive [10, 19] and observed CRU data. We replaced Thornthwaite's potential evapotranspiration with the Penman-Monteith one by modifying accordingly the C++ code presented in [16]. We selected as a baseline for the PDSI computation the reference periods included in the interval 1951–2015, depending on the available data from numerical experiments and/or observations.

In our approach, the observed and simulated components of water cycle (precipitation, potential evapotranspiration, and potential runoff) and the PDSI values were spatially averaged across the studied basins, having in mind that the catchment level is a natural unit. On the other hand, the spatial averaging increases the signal-to-noise ratio while still providing useful information for water resource assessment and management.

The modeling results regarding future evolution of PDSI and its components under RCP scenarios are further used to assess their impact on drought over the catchments under climate change conditions. Usually, there are differences in the climate projections due to model-related biases and natural climate variability. To address this issue, we used the available results from the five-member ensemble taken from EURO-CORDEX archive (**Table 1**) to compute PDSI

components and related indices in the selected case studies. In this context, we analyzed the linear trends of basin-averaged PDSI and potential runoff up to 2100 to assess the impact of climate change on meteorological drought under moderate and worst-case RCP scenarios.

3.1. Validation of Palmer's water balance model at the catchment level

Figure 3 presents the correlation coefficients linking observation-derived components of the Palmer water balance and mean monthly streamflow (Q_{med}) at the gauging stations for each selected basin (Arges, Mures, Prut, Siret, and Someș). Due to data availability constraints, monthly values of ZIND, PRO, and the difference between precipitation and evapotranspiration ($P-PE$) are spatially averaged over the Romanian area of each river catchment, except the Prut basin where the spatial means cover the whole transboundary catchment. The monthly streamflow values are taken from available observations recorded at stations as close as possible to the river outlet. The selection of catchments and stations for streamflow observations

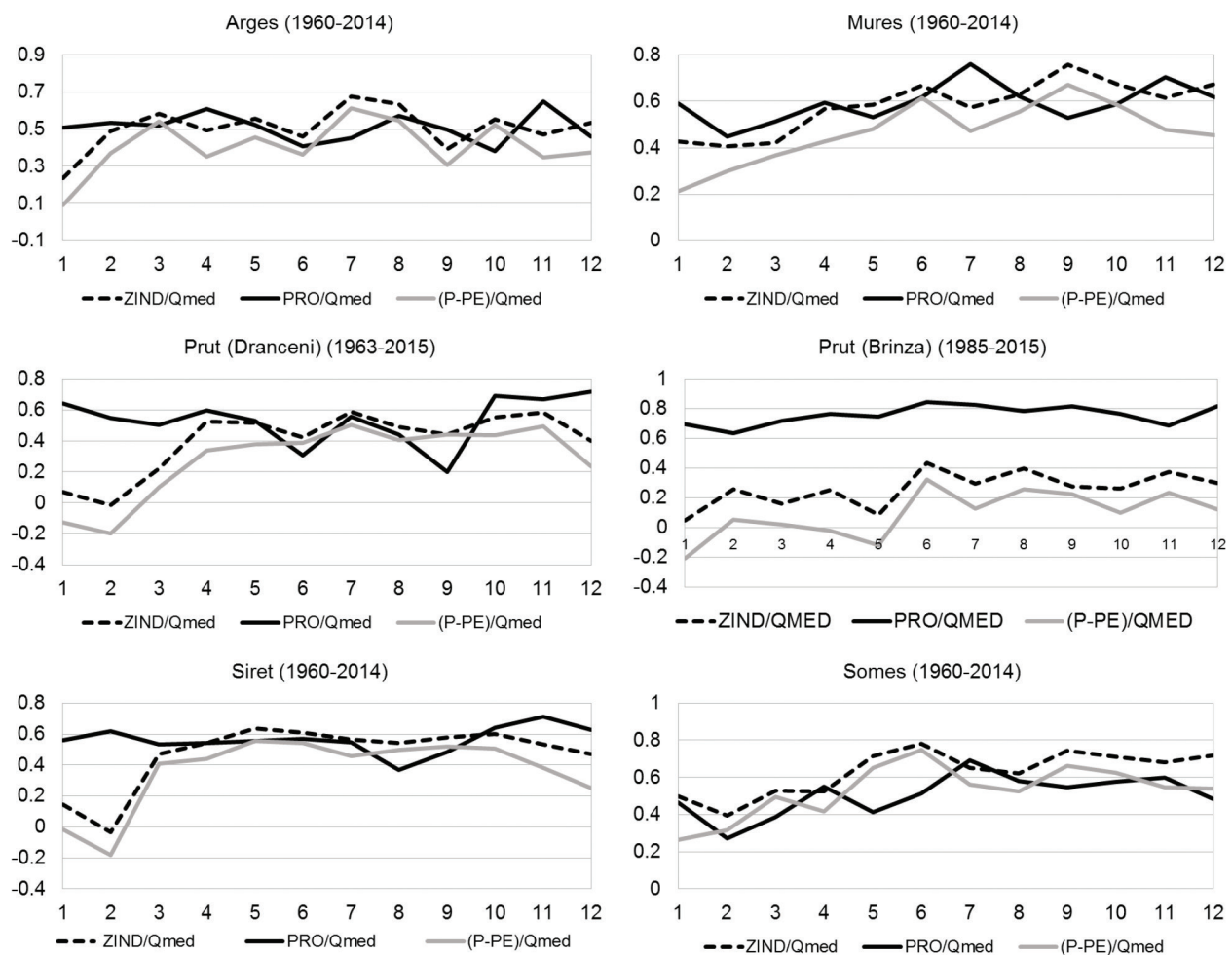


Figure 3. Correlation between monthly components of Palmer Drought Severity Index—soil moisture index ZIND (dotted line) and potential runoff PRO (black line) computed from CRU observations and observed mean monthly streamflow (Q_{med}) at the gauging stations associated for the basins of rivers Arges, Mures, Prut, Siret, and Someș over the Romanian territory. The analyzed intervals with available data are specified in brackets. Gray line illustrates the correlation linking the difference between precipitation and potential evapotranspiration ($P-PE$) and Q_{med} .

was constrained by the data availability—they are mostly over the Romanian territory. In the case of Prut transboundary catchment, we used observations from two hydrometric stations: Dranceni in Romania and Brinza in Republic of Moldova. In general, there are quite large correlation coefficients illustrated in Figure 9 showing that the PDSI represents reasonably well the local process taking place in the analyzed catchments.

An interesting feature is the fact that ZIND correlations with Qmed are systematically larger than the correlation of P-PE with the Qmed, which implies that the Palmer model brings added value in assessing anomalies of the water deficit or surplus (ZIND) compared with the simple difference between precipitation and potential evapotranspiration (P-PE). Also, PRO correlations with Qmed are, in general, larger in cold season months compared to ZIND correlations with Qmed. This can be explained by the fact that the Palmer model does not take snow, frozen soil, and related processes into consideration—the precipitation is immediately transferred into the soil. That is why in winter months, any simultaneously precipitation-related correlations with Qmed are low. On the other hand, PRO depends on soil recharge linked to soil available capacity. Remarkably high correlations all over the year link basin-averaged PRO with Qmed at the Brinza station in the Prut catchment. An explanation could be that Brinza station is very close to the Prut outlet. Streamflows recorded at the Brinza station are integrating the runoff from the whole basin which is not the case for the streamflows recorded at the Dranceni station. However, the time interval used to compute these correlations at the Brinza station is shorter (1985–2015), implying lesser statistical significance. The results presented in **Figure 3** suggest that ZIND and PRO values could be used, at least for certain months and catchments, as simple and robust indicators of anomalies in water cycle components (such as soil moisture and runoff) at the basin level.

4. Results

4.1. Validation of simulated potential evapotranspiration and precipitation for present climate (1970: 2005)

Analyzing together the multiannual averages obtained from observed data and those resulted from the five EURO-CORDEX models (**Table 1**), one can notice that, generally, the seasonal cycles of observed precipitation and potential evapotranspiration are captured by the ensemble of numerical experiments for the present climate (1970–2005). We illustrate here the results for the Prut basin (**Figures 4 and 5**) but the abovementioned conclusion stands for the other basins, too.

In general, the multimodel average simulates very well the observed potential evapotranspiration even though there are some underestimations, especially in spring months.

The results for model-simulated precipitation over the interval 1970–2005 do not reproduce the observed annual cycle as well as in the case of potential evapotranspiration. Even though the simulated annual cycle of precipitation generally resembles the observed one, the monthly values are generally overestimated. Underestimated monthly values are found in some summer months (July and August for the Prut basin).

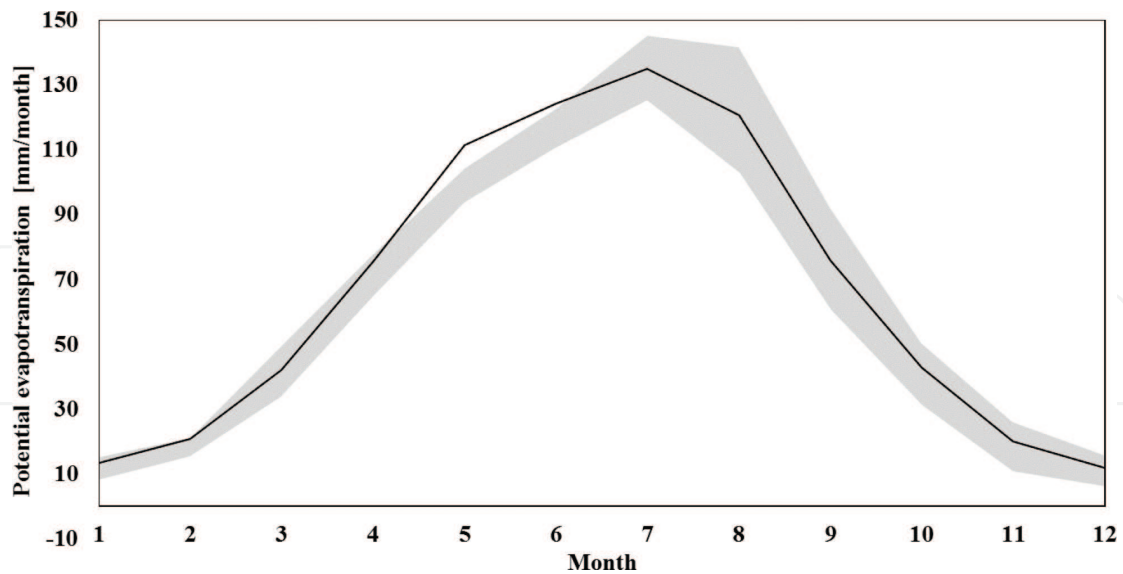


Figure 4. Observed and simulated multiannual means (1970–2005) of monthly evapotranspiration (in mm/month) averaged over the Prut basin. The shaded band illustrates the simulated values from the five-member ensemble of regional climate experiments taken from the EURO-CORDEX archive (see **Table 1**). The black line represents the observation-derived values of potential evapotranspiration based on CRU data.

However, the fact that the multiannual pattern of the two water cycle components (precipitation and potential evapotranspiration) is reproduced, to some extent, by the regional climate models provides a certain level of confidence when analyzing their future evolution and related drought indices in the area of interests under climate change scenarios.

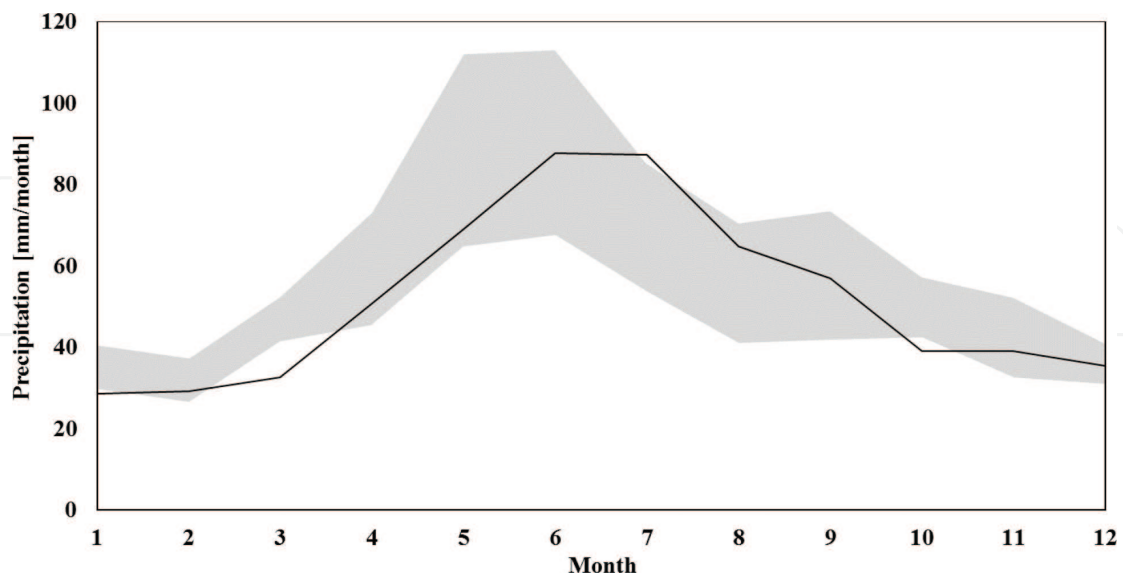


Figure 5. Observed and simulated multiannual means (1970–2005) of monthly precipitation (in mm/month) averaged over the Prut basin. The shaded band illustrates the simulated values from the five-member ensemble of regional climate experiments taken from the EURO-CORDEX archive (see **Table 1**). The black line represents the observation-derived values of potential evapotranspiration based on IMDROFLOOD gridded precipitation data.

4.2. Future projections of water cycle components and climate change impact on drought at catchment level

The main input data for computing the PDSI future projections are from the five-member EURO-CORDEX ensemble presented in **Table 1**.

The linear trend analysis of basin-averaged PDSI computed using the multimodel mean ensemble shows tendencies toward drought conditions over all basins, for both concentration scenarios, more pronounced in the summer months (**Table 2**). Also, as we expected, the trends are larger for higher concentration scenario (RCP 8.5). For instance, in summer months (June to August), the basin-averaged PDSI values are reduced in Arges and Siret basins with 2.98 and 2.67, respectively, over the interval 1970–2100 under RCP 8.5 (**Table 2**). A two-unit decrease in PDSI is consistent with the transition from normal conditions to moderate drought or from moderate to extreme drought. Pronounced decadal variability is also present in the future projections of PDSI under both RCP scenarios (e.g. **Figure 6**). In the Palmer classification [14], depending on the specific climate scenario and catchment, droughts that were deemed as incipient, mild or severe toward the end of the twentieth century will become a normal summer feature toward the end of the twenty-first century. The tendencies for meteorological droughts in summer are coming along with the downward trends of basin-averaged precipitation, potential runoff (and streamflow), and upward trend in potential evapotranspiration. For instance, the largest mean reduction in potential runoff in summer months is for Arges and Siret basins with 36 and 35%, respectively, over the interval 1970–2100 under RCP 8.5 (**Table 2**).

River basin	Climate scenario	PDSI change in 131 years (1970–2100)	PRO change in 131 years (1970–2100) (% of mean PRO computed from 1970 to 2005)
Arges	RCP 4.5	−1.45	−24
	RCP 8.5	−2.98	−36
Mures	RCP 4.5	−0.35	−12
	RCP 8.5	−1.10	−19
Prut	RCP 4.5	−1.45	−23
	RCP 8.5	−1.81	−30
Siret	RCP 4.5	−1.69	−22
	RCP 8.5	−2.67	−35
Somes	RCP 4.5	−0.35	−12
	RCP 8.5	−0.75	−18

Table 2. PDSI mean change (in standardized units) and PRO mean change (in % relative to the mean of the interval 1970–2005) for summer months (June–August) in the interval 1970–2100. Mean values of the five-member ensemble are used.

River basin	Climate scenario	Numerical experiments				
		1	2	3	4	5
Arges	RCP 4.5	-0.75	-2.87	0.20	-2.28	-1.57
	RCP 8.5	0.00	-3.81	-1.85	-4.01	-5.34
Mures	RCP 4.5	1.85	-1.81	0.98	-0.94	-1.89
	RCP 8.5	1.80	-0.31	-2.24	-1.22	-3.58
Prut	RCP 4.5	-2.24	-1.10	-0.43	-1.81	-1.65
	RCP 8.5	-1.14	0.39	-1.89	-2.83	-3.62
Siret	RCP 4.5	-1.69	-1.18	-0.39	-2.75	-2.40
	RCP 8.5	-0.79	-0.55	-1.85	-4.87	-5.27
Somes	RCP 4.5	2.12	-1.93	0.20	-0.75	-1.30
	RCP 8.5	0.83	-0.39	-2.95	0.02	-1.14

Table 3. PDSI change (in standardized units) for summer months (June–August) in the interval 1970–2100.

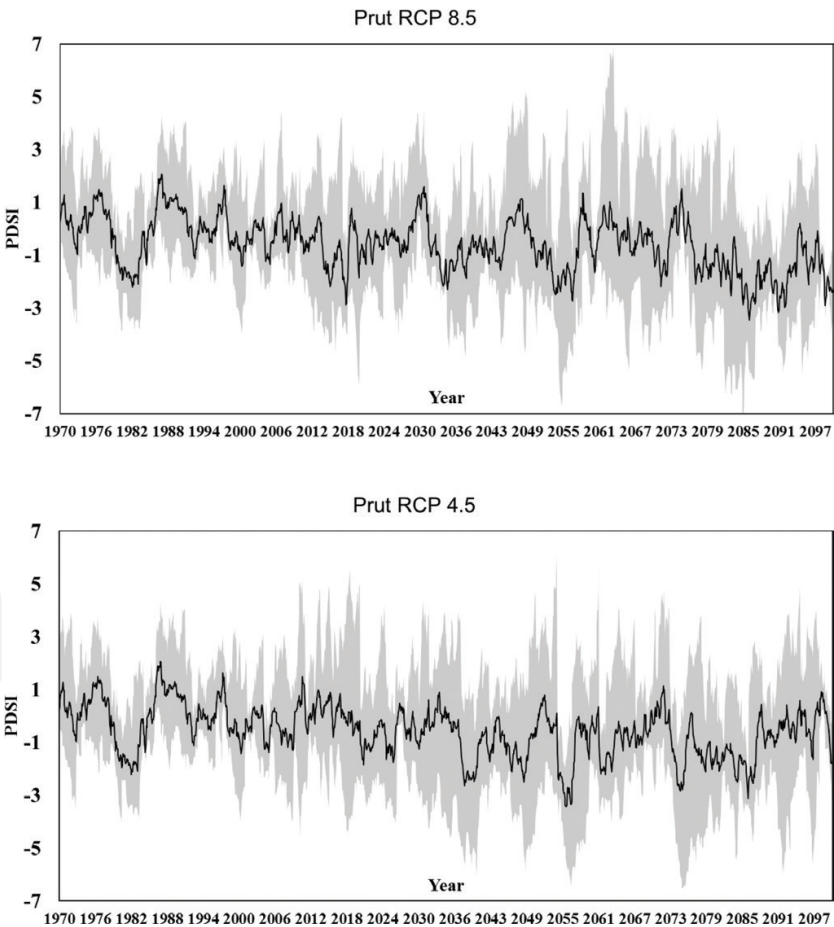


Figure 6. Simulated monthly values (1970–2100) of basin-averaged PDSI over the Prut catchment. The shaded band illustrates the simulated values from the five-member ensemble of regional climate experiments taken from the EURO-CORDEX archive (see **Table 1**). The black line represents the multimodel ensemble mean.

However, when individual evolutions of PDSI values for each numerical experiment are analyzed, the intermodel and internal variability show up revealing cases in which the climate-related signal of drought tendencies is not always present as for the ensemble mean. In **Table 3**, the PDSI changes for the interval 1970–2100 are presented for each numerical experiment listed in **Table 1** and for each river basin. This table illustrates the uncertainty associated with the signal revealed by the ensemble mean. The level of uncertainty related to the summer drought signal seems to be lowest for the Arges river basin if we count, from **Table 3**, the number of experiments for which there are higher PDSI changes in magnitude under the RCP 8.5 than those under the RCP 4.5 (four from five experiments). In this context, the level of uncertainty is highest for the Somes river basin (one from five experiments).

Data are from multimodel means of a five-member ensemble consisting of five numerical experiments (see **Table 1**).

Data are from the five numerical experiments (see **Table 1**).

5. Conclusions

The regional modeling approach we have proposed here provides a base for exploiting simple models such as Palmer water balance in a physical consistent manner: (1) without the need to apply bias corrections and (2) reducing uncertainty by eliminating additional sources of errors which are brought through coupling RCMs with complex hydrological models. Of course, these advantages come with a cost: information provided by our proposed methodology is basin-averaged and cannot account for details at the sub-basin level which could be essential for some specific application.

Our methodological approach is based on two pillars: the Palmer water balance model validated and applied at catchment level and the multimodel ensemble of regional climate experiments (which provides physically consistent information under climate change scenarios). The RCM ensemble analyzed in this chapter manages to reproduce relatively well the observed components of water cycle such as potential evapotranspiration and precipitation when multimodel averages of regional climate results are used over the river basins. These results provide a certain level of confidence when analyzing future evolution of precipitation, potential evapotranspiration, potential runoff and related indices in the area of interests under climate change scenarios.

The correlations between observed streamflow at the observation stations in each basin and PDSI-related indices show that the PDSI represents reasonably well the local water balance and drought-related processes taking place in the catchments (**Figure 3**). This allows us to use the basin-averaged PDSI computed with multimodel ensemble data for the assessment of the climate change impact on drought over the selected basins under the moderate and worst-case concentration scenarios. Spatial average procedure applied here to gridded PDSI provides robust results.

The results from the case studies based on the ensemble means of PDSI suggest that depending on the specific climate scenario and catchment, droughts that in the Palmer classification were deemed as incipient, mild or severe toward the end of the twentieth century, will become a normal summer feature toward the end of the twenty-first century in the mid and lower Danube basin. The tendency toward drought is present under the conditions of a reduction of runoff, mostly in summer, revealing the important role of potential evapotranspiration increase and precipitation decrease in the drought-related processes over the mid-latitude areas. However, the analysis of individual evolution of PDSI in the five numerical experiments, under both climate scenarios, reveals uncertainties associated with the identified signal of enhanced aridity at the basin level. The largest (lowest) uncertainty is found for the Somes (Arges) river basin. More studies that couple local climatic information with their hydrologic impact are needed to provide the background for the assessment of water resources under climate change conditions in terms of adaptation planning and sustainable development.

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Conflict of interest

No conflict of interest is implied in this work.

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