



Article Implementing a Proxy-Basin Strategy to Assess the Transposability of a Hydrological Model in Geographically Similar Catchments

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Abstract: Hydrological modelling is the most common way to investigate the spatial and temporal distribution of regional water resources. The reliability and uncertainty of a model depend on the efficient calibration of hydrological parameters. However, in complex regions where several subcatchments are defined, calibration of parameters is often difficult due to a lack of observed data. The transposability of hydrological models is of critical importance for assessing hydrological effects of land use and climatic changes in ungauged watersheds. Our study implemented a Proxy-Catchment Differential Split-Sample (PBDSS) strategy to assess the transposability of the conceptual hydrological model J2000 in three different subcatchments with similar physiographic conditions in Western Turkey. For dry and wet scenarios, the model was calibrated and validated for five years (2013-2017) in two selected catchments (Kayirli and Ulubey). Afterwards, it was validated by predicting the streamflow in the Amasya catchment, which has similar physical and climatic characteristics. The approach comprises transferring J2000 model parameters between different catchments, adjusting parameters to reflect the prevailing catchment characteristics, and validating without calibration. The objective functions showed a reliable model performance with Nash-Sutcliffe Efficiency (E) ranging from 0.72 to 0.82 when predicting streamflow in the study subcatchments for wet and dry conditions. An uncertainty analysis showed good agreement between the ensemble mean and measured runoff, indicating that the sensitive parameters can be used to estimate discharge in ungauged catchments. Therefore, the J2000 model can be considered adequate in its transposability to physically similar subcatchments for simulating daily streamflow.

Keywords: proxy-catchment differential split-sample; hydrological modelling; transposability; Buyuk Menderes Watershed; calibration

1. Introduction

Hydrological models are powerful tools to represent hydrological quantities and their physical processes on micro and macro scales. They conceptualize and model a hydrological system's processes and characteristics to describe the system's response to environmental conditions [1]. Local or regional hydrological modelling is based on parameters that are controlling coefficients of the model performance. These parameters are defined for primary units (usually grid cells) on physiographic factors, e.g., topography, soil type, and vegetation classes. Their availability depends on observations for calibration and validation in a subset of sites where the model is implemented. The calibration of the model parameters is necessary for simulations to reduce the uncertainty in the parameter ranges and for stability that may directly affect the model' reliability. Hydrological models are often calibrated using observed runoff from catchment outlets (e.g., [2,3]). However, the availability of gauging data is often limited due to costs and management problems of



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). gauging stations, topographical difficulties, ungauged sites, etc. [4]. Model transposability between catchments based on their parameters could be an effective solution for hydrological simulations of ungauged catchments, by taking advantage of catchments' geographical similarity [5,6].

Various studies have investigated model parameter transferability in ungauged catchments [7–11]. Nepal et al. [12] investigated the transferability of the J2000 model in geographically proximate regions. Jin et al. [13] concluded that both proxy-catchment and global mean methods could be used for parameter regionalization in ungauged and geographically similar catchments. Santos et al. [14] applied the SWAT model using the hierarchical testing scheme suggested by Klemeš [15], and assessed the streamflow using the paired t-test and linear regression. Klemeš [15] introduced a model testing scheme of hydrological simulations that suggested the feasibility of the model parameters' geographical transposability within two hydrologically homogeneous regions. As a suitable example, the J2000 model [16] has been widely applied to assess climate and land management's impact on hydrological systems, including streamflow, sediment, and nutrient dynamics at the catchment scale [16,17]. However, its application is challenging due to the controlling parameters required for calibration and validation [18].

For performance evaluation and confirmation of hydrological models, there are four major techniques/tests proposed by Klemeš [15], namely: (a) the split sample test, where the hydrological model is calibrated for one period then tested for another period, (b) the differential split-sample test in which long-term data are divided into two segments that exhibit markedly different conditions. The model is calibrated for one segment and tested for the other. (c) The proxy-catchment test where the model is calibrated in one catchment and validated in another, (d) the proxy-basin differential split-sample test (PBDSS), which is a combination of (b) and (c). In the PBDSS, the long-term data of two catchments is divided into two segments (e.g., wet years and dry years). Then, the model is calibrated two times. First, for one segment in the first catchment and then for the other segment in the second catchment. Each calibration is then validated against the complementary data set. For example, if the model has been calibrated for dry years in Catchment A, it is validated for wet years in Catchment B. After that, the calibration conducted for wet years in Catchment B is validated by modelling dry years in Catchment A [15]. The validation results represent a model's transferability to other geographic and climatic conditions.

The PBDSS examines a model's transposability and its ability to assess the impact of climatic or land use changes in ungauged watersheds. It is often applied to modelling attempts where it is tested whether or not model parameters can be transposed geographically and climatically [3,12,14,15,19]. A broad transferability is a significant objective of most models because it allows to model regions where there is a lack of available runoff observation data. The PBDSS test aims to assess the ability of a hydrologic model to simulate streamflow under different climatic conditions (e.g., wet and dry), which is suitable for use in cases where data are not available [20]. Even though all performance tests described by Klemeš [15] are feasible options, the PBDSS is the most challenging evaluation for a hydrological model that is applied to areas where calibration data are lacking since it tests for non-stationary conditions (e.g., climate change) and can highlight problems [21]. Non-stationary conditions means that data variances and covariances may change due to extreme events or related data inconsistencies over time. Therefore, non-stationary data are difficult to account for in process-based modelling studies. Due to its complication, the PBDSS' validity to examine the transposability of a hydrological model remains poorly quantified [3,20].

Models that can be applied to settings outside of their calibration range are highly needed. In many catchments around the world, changes in land use, demographic changes with changing water demands, and climate changes create novel settings. According to He et al. [22], catchments undergoing significant changes can be considered the same way as ungauged catchments because no past data are available to represent the changed settings. Critical hydrological situations may arise to which farmers and policymakers need to respond, such as shortages of drinking water, irrigation water, or water levels damaging natural ecosystems [23]. Ideally, catchment specific information about such threats including extreme events (i.e., drought) should be available at an early stage to provide decision-makers with the time necessary to adapt management, infrastructure and policies [24–27].

While models need to be able to capture climatic and land use settings for which they were not calibrated, they may also have to be applicable to catchments where no runoff data exists. Due to the high costs of setting up and maintaining gauging stations, it is unrealistic to assume that every subcatchment for which hydrological information is desirable can be gauged. Still, information on streamflow characteristics may be needed in these catchments to enable projects such as the buildings of irrigation infrastructure, dams or hydropower stations [28]. Estimating flows in ungauged catchments can substantially contribute to human welfare by facilitating improved water management that provides a better water supply and safeguards against hydrological threats [29].

Obviously, models that have not been calibrated for the specific catchment and setting to predict streamflow characteristics will perform less reliably than models calibrated with full data availability (see Guo et al. [30] for a recent review of model regionalization). However, such models can still provide invaluable information, e.g., screening for catchments where severe hydrological problems are likely to arise. Further steps should then be taken to improve the reliability and predictive power of the hydrological modelling for these catchments. This could also include building new climate measurement stations and hydrological gauging stations, even though several years of data are usually required for model calibration.

This study implemented a PBDSS test to assess the transposability of the conceptual hydrological model J2000 in three subcatchments of the Buyuk Menderes Watershed in Western Turkey. All three subcatchments are characterized by similar physiographic and climatic conditions. Estimating stream flow spatial and temporal variability is an urgent task for water resource utilization across the river catchments in a water-scarce country such as Turkey. Though estimating the hydrological quantities is an important research question, a limited number of studies have been applied in Turkey to assess conceptual hydrological models' applicability for water resources research [31–33]. The main research challenges were limited data, limited technical background, and complex topography, with many rivers being poorly gauged. These difficulties negatively affect hydrological models' applicability, limiting the regional management of water resources and decision-making. The transposability of models between the catchments allows modellers to conduct model simulations in catchments across the country where the data and parameter gaps are limiting factors. Previous studies [18,31,34] often included detailed hydrological system analyses and model applications at different spatial scales. However, they did not comprise a comprehensive model transposability framework through parameter sensitivities. Therefore, our study is strongly innovative because it assesses the transferability of a process-based hydrological model in a complex mountainous region.

Besides these difficulties, a significant challenge of transferring the hydrological model between the catchments in such regions are the similar sensitivities ranges of the selected parameters. It indicates the possibility of using the sensitive parameters to estimate a discharge in ungauged catchments.

2. Materials and Methods

2.1. Study Area

The three neighbouring catchments Kayirli (964 km²), Ulubey (2285 km²), and Amasya (2747 km²), were selected for the study (Figure 1). These catchments are located at the Buyuk Menderes Watershed which covers approximately 26,000 km² and is the biggest watershed of Western Turkey. While all three catchments are gauged, for the purpose of this study we treated the Amasya catchment as if it were ungauged, modelling its streamflow with a model calibrated in the Kayirli and Ulubey catchments.



Figure 1. Location of the study subcatchments Kayirli, Ulubey, and Amasya located at the Buyuk Menderes Watershed.

The region contains the Buyuk Menderes river with a length of 584 km, which begins in Afyon city and flows into the Aegean Ocean. The selected subcatchments are linked to this river, directly affecting its flow. The sub-tropical climate influences land use and land cover (LULC) pattern in the subcatchments. They are characterized by hills, plains, and needle-leaf forest stands at low and mid-altitudes, mainly European Nut Pine (Pinus pinea) and Black Pine (Pinus nigra), while Oak trees (Quercus cerris) are distributed as broadleaf stands. The Mediterranean climate system dominates the precipitation dynamics, with mild and mostly rainy winters. The selected subcatchments are characterized by steep relief that controls the precipitation distribution and flow dynamics. The primary geological formations include conglomerate recrystallized limestone, meta ultramafic schist, and Jurassic sediments. The region is undergoing agricultural development with consequent trade-offs between field irrigation and flow regimes, and the water supply is of critical importance. The connected valleys and their relief result in both internal circulation of water from evaporation to precipitation, and lateral flows such as runoff, streamflow, and out of basin transfer. The physical properties of the selected subcatchments exhibit strong similarities with regard to climate, relief, and flow conditions.

2.2. Hydrological Model

In our study, we used the process-based J2000 hydrological model [16], which is implemented in the Jena Adaptable Modelling System (JAMS) [35,36]. Process-based models are suitable tools for reliable estimates and prediction of the principal hydrological quantities, namely the contained water amount and the resulting discharge. For the selection of models, it has to be considered that the involved variables in modular structured models which control the flow regimes can have a considerable spatial and temporal variability which needs to be accounted for [37]. Modular approaches provide a better representation of the spatial variability of the flow distribution and a better representation of its internal processes. Due to the increasing explanation of the flow linkages and separate parameters for each module, better transferability and applicability can be expected [35]. The J2000 has a modular structure that comprises modules for estimating hydrologic quantities such as evapotranspiration, snow, soil-water, groundwater recharge, and lateral flow processes in a river system. Figure 2 shows the J2000 model concept. Calibration parameters control the hydrological processes based on parameters for soil, LULC, topography, and geology at the Hydrological Response Units (HRU) level. The spatial resolution of the J2000 is based on the sizes of the HRUs and the various landscape features. Spatially distributed topography data, LULC, soil, and geology are generated into HRUs as primary model entities [11]. Overland flow (RD1), Interflow 1 (RD2), Interflow 2 (RG1), and baseflow (RG2) are the four runoff components produced by the model [18,38]. Process units including infiltration, evapotranspiration, middle pore storage (MPS), large pore storage (LPS), and depression storage structure the soil-water module. In runoff generation, the direct runoff (RD1) has the highest temporal dynamics in a watershed system and comprises the surface and snowmelt runoff. RD2 can be considered as slow direct runoff within the soil zone. Fast (RG1) and slow (RG2) are two basic sub-surface runoff components. RD1 and RD2 are related to retention coefficients (*soilConcRD1* and *soilConcRD2*) and derived from the model entities [39].





The groundwater module calculates the groundwater runoff of all geologic formations in the catchment area, considering different storage and runoff behaviours. Upper- (RG1) and lower groundwater runoff components (RG2) are generated, representing fast and slow flow from the underground reservoirs. They are taken into account as storage retention coefficients, i.e., as factors of the actual groundwater storage content [39]. Reach routing is also an essential factor that transports water from one entity to another in the lower zone until reaching the stream network. The kinematic water approach and Manning and Strickler's velocity were implemented to define reach routing flow processes in the river network of the catchments [16].

2.3. Model Inputs

The J2000 model requires a wide range of data, including LULC, geology, soil type, and topography. The model also utilizes a time-series set comprising meteorological variables (min., max., and mean temperature, humidity, wind speed) and gauging data. The data set

has been selected in an appropriate spatial resolution to reveal the physical characteristics of the study sites in as much detail as possible. Thus, available satellite images (Sentinel-2A) and ancillary data (i.e., DEM), including the best possible resolution, have been selected and used in the study. These images were derived from the National Aeronautics and Space Administration [41] and European Space Agency [42] data portals. A comprehensive set of remote sensing and Geographical Information Systems (GIS) analyses were performed to create the study's required data set for model implementation. The flow observations were obtained from the State Hydraulic Works of Turkey at daily timesteps and formatted according to the model requirements. Both spatial and temporal data sets used in the study are listed in Table 1.

| Data | Data Type | Source | Resolution | Data Description/Properties |
|---|---------------------|---|------------------------------|---|
| | DEM | ASTER GDEM Sentinel-2A | 15 m | Stream network, sub-basins |
| | Satellite images | (4 January 2018, 5 April 2018, 7 June 2018, 22 September 2018) | 10 m | LULC, pan sharpen |
| | LULC | Classified from Sentinel-2A | 10 m | 13 land cover/use classes. 92% (Kappa statistic) |
| Spatial Data | Soils | Derived from Buyuk Menderes Green Atlas Project (supported by the Ministry of Environment of Turkey) | 1/250.000 | 17 soil series Soil physical properties including depth, saturated hydraulic conductivity, texture |
| | Stream networks | Digitized using stream burning method | 15 m | In five stream categories |
| | HRU | Derived using ArcInfo AML | 30 m | Comprising spatial information on heterogeneous units |
| TT 1. | Climate time-series | Turkish State Meteorological Service | 13 stations | Daily temperature, relative humidity, wind speed, precipitation, solar radiation (2013–2017) |
| Hydro- meteorological time-series | Observed flow | State Hydraulic Works of Turkey | Three gauging stations | Flow rates were calculated using this 15 min flow rates (ft3 s-1) to derive mean daily outflow rates (m3 s-1) and daily total (mm) for each sub-basin (Sari, 2018) |

Table 1. Spatial and temporal data set used in the study.

LULC classification was carried out using an object-oriented classification technique, incorporating four Sentinel-2 images, each consisting of six spectral bands. These images were atmospherically corrected and pan-sharpened from 20 to 10 m spatial resolution. The main land cover classes in the subcatchments were categorized as agriculture, forest stands, and bare ground and used in the model. Although numerous meteorological stations are located in the study sites, availability of complete time-series data, including temperature, precipitation, and wind speed, is limited. For model application, we selected a time period with only minor data gaps in terms of meteorological information (2013–2017).

2.4. Calibration and Validation Using Proxy Basin Differential Split-Sample Test

Using the spatial and temporal data set prepared in the data pre-processing step, the J2000 model calibration and validation were carried out daily by performing the hierarchical approach PBDSS proposed by Klemeš [15]. Proxy-catchment tests are a method that reflects a hydrological model's fitness for predicting the impact of land-use and climatic changes [43]. The model was calibrated and validated in two subcatchments in the first step. It was run from 2013 to 2017 for a 5-yr data record for three catchments at the HRU level. The available observed time-series (climate and gauging) data set for Kayirli and

Ulubey subcatchments are divided into two sets based on precipitation conditions, namely wet years (2015–2017) and dry years (2013–2014). Then, we calibrated the model against one of the sets and validated it using a contrasting set. Accordingly, it was first calibrated for wet conditions in the Kayirli subcatchment and then used to simulate streamflow for dry conditions in the Ulubey basin with similar properties and vice versa. Wet and dry periods for the PBDSS test, based on seasonal precipitation for the selected subcatchments during 2013–2017, are shown in Figure 3.



Figure 3. Wet and dry periods of seasonal precipitation for the Kayirli and Ulubey subcatchments during 2013–2017 for the differential split-sample test.

After comprehensive calibration and validation, the model parameters were transferred to the Amasya subcatchment (2013–2017). The model performance statistics were used to select the best range of the calibrated parameters of Kayirli and Ulubey for using in the Amasya subcatchment. The runoff generation and evapotranspiration (ET) were assessed to evaluate and confirm the reliability of model simulations.

2.5. Model Performance Evaluation

For the PBDSS test, the J2000 was calibrated manually to find the parameters that determined the best global water balance results in the subcatchments. The hydrographs were evaluated. The sensitive parameters that affected the flow were selected and revised to reveal the best fit between model simulations and observed flow. Three common performance indicators (goodness of fit) were utilized to assess the model performance, namely the coefficient of determination (\mathbb{R}^2), Nash–Sutcliffe Efficiency (NSE) [44,45], and percent

bias (PBIAS). NSE is commonly used for the performance evaluation of the hydrological models in which PBIAS and R² are representative of the consistency of the trends between simulated and observed values.

NSE varies from negative to 1, where 1 indicates a perfect fit observed and modelled runoff [46]. R² indicates the trend and correlation between the observed and simulated values. It is varied between 0 and 1, and >0.50 is regarded as reasonable for model simulation. The simulated values' tendency to be more or less than their observed counterparts is measured using PBIAS. The reliability of PBIAS values are assessed in three categories as very good (<10%), good (10% < PBIAS < 15%); satisfactory (15% < PBIAS < 25%), unsatisfactory (>25%) [47].

Moreover, we employed a Kolmogorov–Smirnov (p < 0.05) normality test to the streamflow data for defining its consistency. Several goodness-of-fit tests, such as the Anderson–Darling test [48], are used in the literature. The Kolmogorov–Smirnov test is feasible since it compares the overall distributions rather than specific locations or dispersions in the output set. Since it is only applied to continuous distributions, we have selected to apply it to our process-based continuous flow data. The parametric T-paired test was used to assess the correlation between the observed and modelled daily flow, representing the model transposability between the subcatchments [49]. The regression analysis consisted of evaluating simulated and observed streamflow values within four quartiles. Commonly, the first quartile (the least 25% of streamflow) is suggested for use in assessing local water availability for multiple sectoral uses by local authorities and institutions [14].

3. Results and Discussion

3.1. Similarities of the Subcatchment Characteristics

The spatially distributed data sets of Kayirli, Amasya, and Ulubey subcatchments are shown in Figure 4, and their physical characteristics are summarised in Table 2. Transferring the J2000 model parameters was possible due to the physical similarities of the catchments regarding soils, LULC, geology, and topographical characteristics.

Based on the spatial data set, the subcatchments are characterized by a varied topography, ranging from altitudes of 15 m to 2390 m. The mean elevation of Kayirli is slightly higher than that of the Amasya subcatchment, while Kayirli has lower altitude ranges. This is one of the major factors affecting precipitation and runoff direction in the Buyuk Menderes region. Topographical variations were utilized to parameterize the model entities and derive topological linkages for runoff generation and direction.

The time-series data show that the mean annual precipitation of Kayirli (967 mm) is higher than in Ulubey (915 mm) and Amasya (703 mm). The precipitation was measured from the 13 meteorological stations around the subcatchments, providing daily temperature, relative humidity, wind speed, and solar radiation data. The total annual runoff is higher in Kayirli (406 mm) than in Ulubey (262 mm) and Amasya (363 mm). Model simulations show a similar conversion performance from precipitation to runoff for all subcatchments.

LULC characteristics comprise needle-leaf and broadleaf forest formations, and meadows. Agricultural lands covered 13% of Kayirli, 22% of Amasya, and 29% of Ulubey. Soils are clayey and include red-brown soils and brown-forest soils, corresponding to the elevation zones based on the soil taxonomy of the Food and Agricultural Organization (FAO) [50] (Figure 4).

Based on the physical similarity, the catchments are ideal testbeds to examine and evaluate the performance of a process-based model in terms of its parameter-based transposability in neighboring subcatchments [18,34].

Kayırlı 10 20 ⊒ km Amas 0 10 20 Ulubey Soil Geology Land use/cover Calcare Reddish brown soils Karbonifer Jurasik Coniferus forest Citrus Permiyen Alluvial coastal soils Red mediterranean soils Decidious forest Wetlands Pliyosen Devonien Kuvaterner Organic soils Reddish brown Mediter. soils Grassland Salty dunes Eosen Oligosen Paleosen Alluvial soils Chestnut soils Bareground Water Kretase Kambriyen Siluriyen Brown soils Hydromorphic soils Rainfed agriculture Urban Miyosen Triyas Reddish maroon soils Calcareous b wn forest soi Irrigation agriiculture

Figure 4. Soils, LULC, and geology maps of the Kayirli, Ulubey, and Amasya subcatchments.

| Free characteria (Characteria ting | Catchments | | | | | |
|------------------------------------|---|---|---|--|--|--|
| Ecophysical Characteristics - | Kayırlı | Amasya | Ulubey | | | |
| Area (km ²) | 964 | 2747 | 2285 | | | |
| | LULC | (km ²) | | | | |
| Needleleaf forest | 567 | 1615 | 1094 | | | |
| Broadleaf forest | 22 | 111 | 247 | | | |
| Meadows | 191 | 347 | 127 | | | |
| Bare ground | 31 | 39 | 104 | | | |
| Agriculture | 134 | 624 | 678 | | | |
| 5 | Soils | (km ²) | | | | |
| Red-brown | 373 | 1081 | 1700 | | | |
| Brown forest | 269 | 650 | 100 | | | |
| Red Maroon | - | - | 223 | | | |
| | Geo | logy | | | | |
| | Mainly conglomerate recrystallized limestone, meta-ultramafic schist, and Jurassic sediments | Mainly conglomerate quartzite, recrystallized limestone, meta-ultramafic schist | Mainly conglomerate quartzite, recrystallized limestone, meta-ultramafic schist | | | |
| | Climate and fl | ow conditions | | | | |
| Precipitation (mm) | 967 | 915 | 703 | | | |
| Temperature (°C) | 15.0 | 15.0 | 15.5 | | | |
| Obs. runoff (mm) | 406 | 363 | 262 | | | |
| Elevation (m) | | | | | | |
| Mean | 730 | 1000 | 1087 | | | |
| Maximum | 1886 | 2390 | 2240 | | | |
| Minimum | 272 | 152 | 552 | | | |
| Slope (%) | 21 | 20 | 12 | | | |

| Table 2. | Ecophysical | characteristics | of the su | ubcatchments. |
|----------|-------------|-----------------|-----------|---------------|
| | | | | |

3.2. Transferring Model Parameters

Each module of the model contains several module parameters. A total of 30 calibrated parameters were utilized in J2000 simulations of the Kayirli, Ulubey, and Amasya subcatchments. Table 3 shows calibration parameters that were optimized to improve model performance. Five parameters, namely *soilConcRD2*, *soilConcRD1*, *soilMaxInfWinter*, *soilMaxInfSummer*, *baseTemp* were found to be more influential for the model outputs. The rationale for selecting the parameters set was based on manual analysis (trial and error) and Monte-Carlo simulations as described in Nepal et al. [36]. Moreover, the model entities comprise the ecophysical complexity of the subcatchment landscape (slope, elevation, and aspect), vegetation (e.g., leaf area index and rooting depth), soil (field capacity and LPS), and geology (water storage capacity of aquifers and retention period) [51]. These are connected and compiled in the HRU parameter file in which calibration parameters control the hydrological processes on a topological basis.

Table 3. Calibration parameters in J2000 simulations.

| Parameter | Description | Global Range | Calibrated (Kayirli) | Calibrated (Ulubey) |
|----------------------------|--|--------------|-------------------------|------------------------|
| Soil-Water module | | | | |
| soilMaxDPS (mm) | maximum depression storage | 0 to 10 | 5.10 | 7.78 |
| soilLinRed | linear reduction co-efficient for AET | -5 to 5 | 4.91 | 3.47 |
| soilMaxInfSummer (mm) | maximum infiltration in summer | 0 to 200 | 100 | 26.53 |
| soilMaxInfWinter (mm) | maximum infiltration in winter | 0 to 200 | 96 | 55.85 |
| soilMaxInfSnow (mm) | maximum infiltration in snow-covered areas | 0 to 200 | 104 | 124 |
| soilImpGT80 | infiltration for areas greater than 80% sealing | 0 to 1 | 0.54 | 0.62 |
| soilImpLT80 | infiltration for areas lesser than 80% sealing | 0 to 1 | 0.53 | 0.86 |
| soilDistMPSLPS | MPS-LPS distribution coefficient | 0 to 10 | 3.1 | 4.83 |
| soilDiffMPSLPS | MPS-LPS diffusion coefficient | 0 to 10 | 5.7 | 7.60 |
| soilOutLPS | outflow coefficient for LPS | 0 to 10 | 5.0 | 6.31 |
| soilLatVertLPS | the lateral vertical distribution coefficient | 0 to 10 | 4.5 | 3.15 |
| soilMaxPerc (mm) | maximum percolation rate to groundwater | 0 to 100 | 50 | 33.16 |
| soilConcRD1Flood | recession coefficient for a flood event | 0 to 10 | 7.0 | 4.15 |
| soilConcRD1Floodthreshold | the threshold value for soilConcRD1Flood | 0 to 500 | 500 | 430 |
| soilConcRD1 | recession coefficient for overland flow | 0 to 10 | 2.9 | 8.04 |
| soilConcRD2 | recession coefficient for Interflow | 0 to 10 | 3.4 | 5.09 |
| Precipitation distribution | | | | |
| module | | | | |
| Trans | threshold temperature | 0 to −5 | 1.1 | 1.5 |
| Trs | base temperature for snow and rain | -5 to $+5$ | 0.0 | 0.0 |
| Interception module | 1 | | | |
| α_rain (mm) | storage capacity (m ²) of particular land cover for rain in mm | 0 to +5 | 1.3 | 2.3 |
| a_snow (mm) | storage capacity (m ²) of specific land cover for snow in mm | 0 to +5 | 1.7 | 2.0 |
| Snow module | | | | |
| snowCritDens (%) | critical density of the snowpack | 0 to 1 | 0.381 | 0.451 |
| snowColdContent | cold content of the snowpack | 0 to 1 | 0.0012 | 0.01 |
| baseTemp (oC) | the threshold temperature for snowmelt | -5 to 5 | 0 | 0 |
| t_factor | melt factor by sensible heat | 0 to 5 | 2.84 | 3.10 |
| r_factor | melt factor by liquid precipitation | 0 to 5 | 0.21 | 0.34 |
| g_factor | melt factor by soil heat flow | 0 to 5 | 3.73 | 2.75 |
| Groundwater module | | | | |
| gwRG2Fact | factor for runoff dynamics of RG2 | 1 to 5 | 0.84 | 2.69 |
| | calibration coefficient for distribution of | 1 (. E | 1.0 | 2.44 |
| KG1KG2alst | percolation water | 1 to 5 | 1.0 | 3.44 |
| gwRG1Fact | factor for runoff dynamics of RG1 | 1 to 5 | 1.0 | 2.50 |
| gwCapRise | factor for the setting of capillary rise | 1 to 5 | 1.0 | 1.98 |

Figure 5 shows the comparison of the selected parameters in the study subcatchments. The parameter ranges were weighted to define their sensitivity to the model accuracy. The weights ranged between 0.01 to 0.23, with highly sensitive parameters having a weight closer to 0.23. The average weight was 0.058, and the parameters with weights smaller than the average were defined as "less sensitive". The J2000 model was susceptible to soil-water module parameters (*soilConcRD1, soilConcRD2, soilMaxPerc*) in line with Donmez et al. [18] for streamflow. Remarkably, the J2000 model was very sensitive to *soilConcRD2*, which had a weight of 0.23 for Kayirli and of 0.14 for Ulubey. *SoilConcRD2* is the retention coefficient for interflow and controls the amount of water moving to interflow. Furthermore, *soilMaxInfSummer* was also sensitive in Kayirli and Ulubey subcatchments, with weights of 0.09 and 0.16, respectively. This parameter is essential in the soil-water module and limits the maximum infiltration during the summer period.



Figure 5. Comparison of the sensitivity of the selected parameters in three subcatchments for NSE.

The storage capacity (m^3) of a particular land cover for rain (*g_rain*) showed considerable sensitivity. There was a remarkable difference in maximum infiltration in summer (*soilMaxInfSummer*) and maximum infiltration in winter (*soilMaxInfWinter*) parameters between Kayırli and Ulubey subcatchments due to the saturation levels based on soil characteristics. The maximum percolation rate to groundwater (*soilMaxPerc*), which has a default value range of 0–100, was calibrated to 50 and 33.16, respectively. The most remarkable differences were found in soil parameters *soilConcRD1* and *soilConcRD2*, which control overland and interflows based on the varied spatial variability and soil depth in both subcatchments. The calibration of groundwater was controlled by the factor for runoff dynamics, namely RG1 (*gwRG1Fact*) and RG2 (*gwRG2Fact*). These parameters influenced the amount of water moving from the shallow to deeper aquifer zones, directly affecting the total runoff generation of the subcatchments. Notably, the parameters used in the soil-water module were recognized as sensitive and can strongly affect the model hydrograph. The sensitivity range of the parameters is given in Table 4. It represents the efficiency of the parameters in model simulations.

| Parameters | Low Range | High Range |
|------------------|-----------|------------|
| gwRG1Fact | 0.03 | 4 |
| gwRG1RG2dist | 0.04 | 4 |
| gwRG2Fact | 0.01 | 5 |
| soilConcRD1 | 5 | 10 |
| soilConcRD1flood | 0.01 | 7 |
| soilConcRD2 | 5 | 10 |
| soilLatVertLPS | 0.03 | 6 |
| soilLinRed | 0.07 | 5 |
| soilMaxInfSummer | 0.08 | 3 |
| soilMaxInfWinter | 0.08 | 3 |
| soilMaxPerc | 0.04 | 4 |
| flowRouteTA | 10 | 50 |
| baseTemp | 0.1 | 8 |
| t_factor | 1 | 50 |
| snow_trs | 0.03 | 8 |

Table 4. Sensitivity ranges of the selected parameters.

Addressing the parameter sensitivity intervals, six out of fifteen parameters were above the average sensitivity range for NSE analysis in three regions overall. Snow parameters, including t_factor and *snowtrs* were the least sensitive parameters for the study subcatchments. This was due to sub-tropical climatic conditions of the study site and, therefore, a low amount of snow patterns so that the temperature factor for calculating snowmelt runoff would only have a small effect on model simulations.

3.3. Proxy Basin Differential Split-Sample Test

After defining the parameter ranges, we implemented the PBDSS test to assess the transposability of the conceptual hydrological model J2000 in Kayırlı, Ulubey, and Amasya subcatchments. The J2000 hydrological model was calibrated and validated for five years (2013–2017) in Kayırlı and Ulubey for dry and wet scenarios and validated in Amasya. The calibrated and validated parameters of the Kayırlı and Ulubey subcatchments were transferred to the Amasya to enable the model transposability.

First, dry and wet periods of calibration subcatchments were separated for carrying out the PBDSS test. For daily scales, the wet and dry years for Kayirli and Ulubey were split based on climate data for calibration (2013–2014) and validation (2015–2017). After calibration and validation, the model parameters were transferred to the nearby Amasya subcatchment for validation (2013–2017). The model showed a good fit (Figure 6) and agreement between simulated and observed flows (Table 5), although it was observed that peaks were underestimated during both calibration and validation periods.

Kayirli, Ulubey, and Amasya subcatchments show strong similarities in terms of their ecophysical characteristics. For the Kayirli subcatchment, the model's performance was successful, although the streamflow was underestimated in the calibration period. The first year of the calibration period in 2013 exhibited a remarkable underestimation of the streamflow, associated with rainfall distribution and elevation inconsistencies in mountainous regions due to their spatial and temporal representation in the model [52]. Validation for Kayirli showed a great fit between observed and modelled flow values in the three years from 2015 to 2017. The J2000 model also showed a good performance for the Ulubey subcatchment, although there were slight overestimations of streamflow in the calibration and early in the validation period. Overall, the model results provided useful daily flow simulations and had a satisfactory hydrograph for calibration data and an even better performance for the validation data.



Figure 6. Simulated and observed streamflow hydrograph of the (**A**): Kayirli, (**B**): Ulubey (calibration: 2013–2014), and (**C**): Amasya (validation: 2013–2017).

The objective functions showed that the J2000 represented the observed flow behaviour during calibration and validation periods reasonably well, albeit slightly under- and overestimating peaks. The E values were computed from daily results as 0.72 and 0.82 for dry and wet periods of the Kayirli subcatchment. The R^2 of the same subcatchment was 0.75 and 0.81, while the streamflow trends were captured reasonably well. The PBIAS indicated that the model had a 2–5% deviation between the simulated and observed flow in the calibration and validation periods. The model achieved similar results for the Ulubey subcatchment, where the E values of the simulated flows were 0.74 and 0.73 for dry and wet periods. Some studies showed that the model efficiency was consistently lower in the dry periods than in the wet periods [53]. The model's daily flow trends were also captured, as indicated by R^2 values higher than 0.73.

| Periods | Discharg (m | e Average ³ /s) | Performance Indicators (Daily) | | |
|-------------------------|----------------|-------------------------------|--------------------------------|-------|-----------------------|
| T CHOUS | Observed | Simulated | NSE | PBIAS | R ² |
| Kayırlı—Dry (2013–2014) | 6.623 | 3.740 | 0.72 | 3.53 | 0.75 |
| Kayırlı—Wet (2015–2017) | 10.764 | 12.102 | 0.82 | -2.45 | 0.81 |
| Ulubey-Wet (2013-2014) | 7.227 | 6.742 | 0.74 | 3.71 | 0.73 |
| Ulubey—Dry (2015–2017) | 4.030 | 4.510 | 0.73 | -1.91 | 0.77 |
| Amasya (2013–2017) | 15.504 | 20.085 | 0.76 | -2.86 | 0.82 |

Table 5. PBDSS test model performance indicators for simulated and observed streamflow in the Kayirli, Ulubey, and Amasya subcatchments (E: Nash–Sutcliffe efficiency, PBIAS: percent bias, R² determination coefficient).

Although the efficiency results indicated a good relationship between observed and simulated flow, there are short under and overestimation periods in the Amasya subcatchment. These slight differences in simulation peaks can be due to several reasons, including, e.g., the conceptualization of the model's modules for hydrological extremes, rainfall anomalies, and missing meteorological stations in high-elevated regions [51,54].

The results of the PBDSS test show that the model simulated the streamflow in the Amasya considerably well, using the calibrated and validated parameters from the Kayirli and Ulubey subcatchments. The dotty plot between observed and simulated daily flow for the Amasya indicates a good correlation for four quartiles ranging from 0.79 to 0.85 in 456 sample days. In Amasya, the highest agreement was captured between 15 and 90 m³/s in the fourth quartile. Overall, R² for Amasya was 0.78, indicating an even better fit than in Kayirli (0.75).

The PBDSS test applied in the study allowed us to evaluate the hydrological model's ability to predict the flow generation in data-scarce regions for validation. Accordingly, the performance of the J2000 was assessed in the Amasya subcatchment for validation. The model seemed to represent a good correlation between simulated and observed flows. after transferring the parameters from the multiple calibration phase in Kayirli and Ulubey catchments. The E value of 0.76 for daily simulations during the validation period indicated this correlation clearly. With regard to PBIAS, the model overestimated streamflow by 2–3% during wetter years in the calibration period and underestimated streamflow by approx. 3% overall. However, this performance can be considered appropriate for simulating streamflow in a mountainous sub-tropical subcatchment. Overall, the model provided satisfactory results in Kayirli, Ulubey, and Amasya subcatchments during calibration and validation, and excellent performance with regard to capturing daily trends of temporal streamflow distribution.

3.4. Assessing the Streamflow Estimations and Model Transposability

After model calibration and validation processes, the runoff generation and evapotranspiration (ET) were assessed to evaluate and confirm the reliability of model simulations (Table 6). Runoff generation was the primary output consisting of three different flow contributions, including surface flow (RD1), sub-surface flow (RD2), and base flow (RG1) in the three subcatchments.

Table 6. Water balance in Kayirli, Ulubey, and Amasya subcatchments based on the simulation outputs (2013–2017).

| | Hydrological Variables (mm) | | | | | | |
|---------------|-----------------------------|-------|-------|-------|------|-------|--|
| Subcatchments | PrecipitationRunoff | | RD1 | RD2 | RG1 | ET | |
| Kayirli | 967.3 | 433.9 | 173.5 | 108.4 | 86.8 | 601.6 | |
| Ulubey | 703.8 | 294.0 | 123.5 | 67.6 | 58.8 | 528.2 | |
| Amasya | 915.2 | 398.9 | 139.6 | 99.7 | 95.7 | 569.4 | |

The precipitation and runoff ratio ranged between 28–40%, compatible with other semiarid regions in Turkey [55]. Runoff estimations varied between 294 and 433 mm. In all subcatchments, the highest amount of the simulated runoff occurred as surface flow. The highest ET was estimated as 601 mm for the Kayirli subcatchment, though the difference between the subcatchments was small. Baseflow and sub-surface flow reached 9 to 12% of the total annual precipitation amount, vital for contributing to river flow throughout the year.

To confirm the model's transposability between the subcatchments, the simulation results for each subcatchment were compared using regression analysis. Daily simulated and observed runoff values were separated by quartiles and correlated for 2013–2017 (Figure 7).



Figure 7. The correlation between simulated and observed streamflow in 2013–2017 by regression analysis (**A**): first quartile (0–24%), (**B**): second quartile (25–49%), (**C**): third quartile (50–74%), (**D**): fourth quartile (75–100%).

The observed hydrological data in Turkey's watersheds is quite limited, making modelling studies difficult. The outcomes of our research indicate a valuable alternative in data-scarce regions with incomplete or non-existent gauging data. Regarding model transposability evaluation, the correlation levels with R^2 indicated a good agreement between the simulated and observed runoff of the subcatchments for all four quartiles. The J2000 slightly overestimated the minimum flow for the first quartile in the Amasya subcatchment (A3); however, the R^2 of 0.82. is quite satisfying. It underestimated the

second quartile of the simulated flow of Kayirli (B1). Table 7 shows the results of the paired t-test and regression analysis for observed and simulated daily runoff, divided by quartiles.

| Gauge | Quartile | n | t _{calculated} | R ² | Difference | <i>p</i> -Value |
|---------|-------------|-----|-------------------------|-----------------------|------------|-----------------|
| | 1° | 456 | -0.94 | 0.896 | -0.0403 | 0.348 |
| Varunlı | 2° | 456 | -0.15 | 0.698 | -0.0047 | 0.878 |
| Kayirii | 3° | 456 | -0.91 | 0.682 | -0.153 | 0.365 |
| | 4° | 458 | 2.44 | 0.694 | 1.619 | 0.015 |
| | 1° | 456 | 0.12 | 0.919 | 0.0021 | 0.908 |
| Illubor | 2° | 456 | -1.07 | 0.834 | -0.0258 | 0.286 |
| Olubey | 3° | 456 | -1.14 | 0.846 | -0.0618 | 0.256 |
| | 4° | 458 | 1.44 | 0.853 | 0.395 | 0.150 |
| | 1° | 456 | 0.12 | 0.795 | 0.0021 | 0.908 |
| Amagua | 2° | 456 | -1.07 | 0.766 | -0.0258 | 0.286 |
| лпабуа | 3° | 456 | -1.14 | 0.776 | -0.0618 | 0.256 |
| | 4° | 458 | 1.44 | 0.855 | 0.395 | 0.15 |

Table 7. Outputs of the regression analysis and paired *t*-test on observed and simulated flows n—number of sample value; $t_{calculated} = paired t$ -test, calculated value; difference; the difference between observed and simulated flow in respective quartile.

The simulation results suggested that the calibrated and validated J2000 parameters are transferable to other catchments with similar physiographic conditions, corroborating the findings of Nepal et al. [51]. We conclude that (a) the catchments with high physical similarity in terms of its landscape variability and functioning, have similar hydrological responses, in line with Nepal et al. [12]; and (b) the J2000 is suitable for modelling the three similar catchments investigated in this study and for transferring parameters to reproduce their similar hydrological response. The J2000 model can thus be calibrated in one or more catchments, and its calibrated parameters can be transferred to model an ungauged catchment with similar conditions. Bárdossy [28] and Blöschl [56] found similar results, indicated that the physically similar catchments are likely to apply a hydrological model using transferred parameters from proxy catchments.

The model simulations had reasonable objective function outputs (>0.70). Therefore, this statement indicated that the structure of the model is suitable enough to capture the catchment response in similar regions. We have applied an uncertainty analysis that showed a good agreement between the ensemble mean (multiple model runs) and measured runoff that is the range of the parameter uncertainty band. Thus, the results show the transferability of the parameters of the J2000 hydrological model to physically similar catchments are doable. Moreover, the results are expected to enable improved water resources management on a catchment scale. The evaluation (calibration) technique is transposable to other semi-arid regions in Turkey and the world.

Donnelly [57] found that the model performed significantly better when modelling multiple catchments if the PBDSS approach is used in the calibration process. This is due to its capability to enhance the calibration performance of the model that contributes to the selection process of various calibrated parameter sets for best use in the ungauged watershed.

4. Conclusions

Employing the J2000 model, we performed a PBDSS test using a set of parameters of the Kayirli and Ulubey subcatchments for five years (2013–2017). Parameters were calibrated and validated in these two subcatchments in the simulation period. Then, the J2000 was validated in the Amasya subcatchment to confirm its transposability to reproduce the daily streamflow. The J2000 results for improving management and streamflow planning are carried out by analyzing runoff generation based on its observed and simulated values. The main findings of the study can be summarised as follows:

- In the Amasya subcatchment that had been treated as if it were ungauged, the performance indicators resulted in E values higher than 0.76 for daily streamflow, indicating a good performance at the daily scale and confirming the model transposability between the subcatchments. Hence, the PBDSS showed that the calibrated parameters were transposable to other subcatchments with a similar landscape. Likewise, the paired t-test and the regression analysis between the observed and simulated flow indicated that the J2000 is suitable to estimate daily streamflow in different subcatchments that showed its viability to implement even in non-stationary conditions. Moreover, the simulation hydrographs reflected that the model could also be a valuable tool to provide dynamics stream flow outputs for regional water management processes.
- The transferred parameters of the model from Kayirli and Ulubey were directly used in the validation process in the Amasya subcatchment without any further adjustment. In the case of a manual adjustment attempt (e.g., percolation ratios, soil saturation), the simulated results might be improved further.
- The study showed the model's capability to transfer to proximate subcatchment in the proximity basins. This argument was also pointed out in Beven [58] and Van der Linden [3] a parameter set could be used for similar defined conditions.
- The model showed a good performance after transferring the model parameters from Kayirli to the Amasya subcatchment. Since the sizes of both subcatchments showed a remarkable difference, the effect of catchment size on the parameter values can be ignored in parameter transferability between subcatchments. In other words, the parameters derived for a smaller area represent the averaged physical conditions of the greater subcatchment in its modelling process.
- Parameter variation, therefore the model performance could change in different study regions with different physical characteristics. We did not assess model transposability through the calibrated parameters in physically different regions. Follow up research should focus on determining the controlling capacity of model parameters in physically different areas, and therefore, the potential transferability of the model to different regions.
- Since the parameters might differ due to the physical structure (e.g., geology, soils, land cover), future studies should also focus on exploring the model's capability to estimate streamflow in physically different catchments. Therefore, the model could be applied to different subcatchments with different climatic and physical conditions to examine its suitability in various conditions.
- Some of the hydrological models' parameters are affected by the incomplete representation of the topography in the catchments. Since the topographical variations directly affect the water movement, routing parameters (e.g., flow routing) might influence the model performance. Thus, a focus could be given to applying the model in topographically varied catchments, and a reliable comparison could be made in model performance between flat and mountainous regions.

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