Chapter 17
Ecohydrological Modeling and Scenario Impact Assessment in Rural Rio de Janeiro

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Abstract Understanding hydrological process dynamics is a crucial requirement for river basin management and environmental planning. Possible future climate changes raise questions about their impact on human livelihoods, which strongly depend on water availability and quality, soil fertility, and other ecosystem services. This chapter presents a physically based, spatially distributed ecohydrological model that was applied within three meso- to macroscale watersheds in the hinterland of Rio de Janeiro. While an increasing population and a fast-growing industrial sector create a high demand for water supply, the study region faces serious problems of forest fragmentation, overexploitation, and soil degradation, which create increasing pressures on water resources. This situation is further intensified by the climate conditions with distinct wet and dry periods that can cause floods and landslides in the rainy season and water shortages during dry periods, especially affecting the agricultural and domestic supply sectors. Recent water shortages raise questions how future climate changes will impact the hydrological dynamics and if river basin management needs to take appropriate counteractions. The results show that the developed models allow simulating hydrological processes at a high spatiotemporal resolution. Given the fact that their process representation is physically based, these models can help answer questions about hydrological dynamics under changing environmental conditions.

Keywords Ecohydrological modeling · System analysis · Scenario assessment · Climate change · Atlantic Forest

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17.1 Introduction

Brazil is one of the countries with the largest freshwater resources in the world (WBCSD 2006). However, during the years 2014 and 2015, the southeastern area of the country experienced a severe water shortage, also described as water collapse (Dobrovolski and Rattis 2015) in two of the biggest metropolitan regions in the country, Sao Paulo and Rio de Janeiro, with altogether around 32 million inhabitants.

The metropolitan region of Rio de Janeiro with approx. 12 million inhabitants is still growing. This growth attracts more and more industry and agricultural corporations within the hinterland of the city to meet the increasing economic demands. Thus, the pressure on water resources is becoming crucial and is visible, e.g., by reservoirs and hydropower plants or increasing agricultural production within the region. Despite rising water withdrawals and pollution, the region still lacks water provision plans, water system infrastructure, and adequate political management, also described as hydrosocial scarcity (Britto et al. 2016).

The challenges related to these conditions are further intensified by the hydroclimatological factors. The region possesses distinct wet and dry periods that can cause floods and landslides in the rainy season as well as water shortages during dry periods, especially affecting the agricultural and domestic supply sectors. A sound river basin management that would safeguard the various water-related ecosystem functions and services requires an evaluation of the ecohydrological system to understand the extent of the related process alteration. Due to their explicit representation of involved processes and related interactions, physically based computer models can provide valuable help to understand complex, interlinked systems. Because of their predictive capabilities and the option to evaluate the impacts of future development scenarios, e.g., changing land use patterns or climate conditions, they are often used to support decision-making processes (Bossel 2004). Process-based ecohydrological models are therefore adequate tools to verify the current understanding of the observed system as well as to quantify and predict hydrological dynamics on a specific spatiotemporal scale.

The overall objective of the study presented here was to understand the ecohydrological system and develop a transferrable ecohydrological modeling platform that can be applied in the whole Rio de Janeiro state (RJ). More specifically, one objective was to develop physically based, spatially distributed ecohydrological models with high spatiotemporal resolutions within different meso- to macroscale pilot watersheds that are representative for the rural parts of the state. Based on these models, another objective was to simulate and evaluate the impact of climate change scenarios on the hydrological dynamics within river basins to answer questions about water availability and occurrence of extreme events in the future. Different Earth system models (ESM) and scenarios were used to set the boundary conditions for this objective.

17.2   Data and Methods

The choice of data and methods was based on the following additional objectives: (i) identify study areas that represent the environmental conditions and land management that are dominant in RJ, (ii) select a hydrological simulation model that represents the controlling hydrological and management processes on a high spatio-temporal resolution, and (iii) hydrological system understanding to properly parameterize the selected models. This section describes the chosen data and methods.

17.2.1   Study Area

To address the objectives listed above, three meso- to macroscale basins were selected for the model applications to represent the ecohydrological conditions throughout the rural parts of RJ (see Fig. 17.1):

1. The Guapi-Macacu River basin (GMRB) is located close to the metropolitan region of Rio de Janeiro and Niterói and covers an area of 1,265 km^2. The land use is dominated by forest and pasture. The climate varies from a maritime
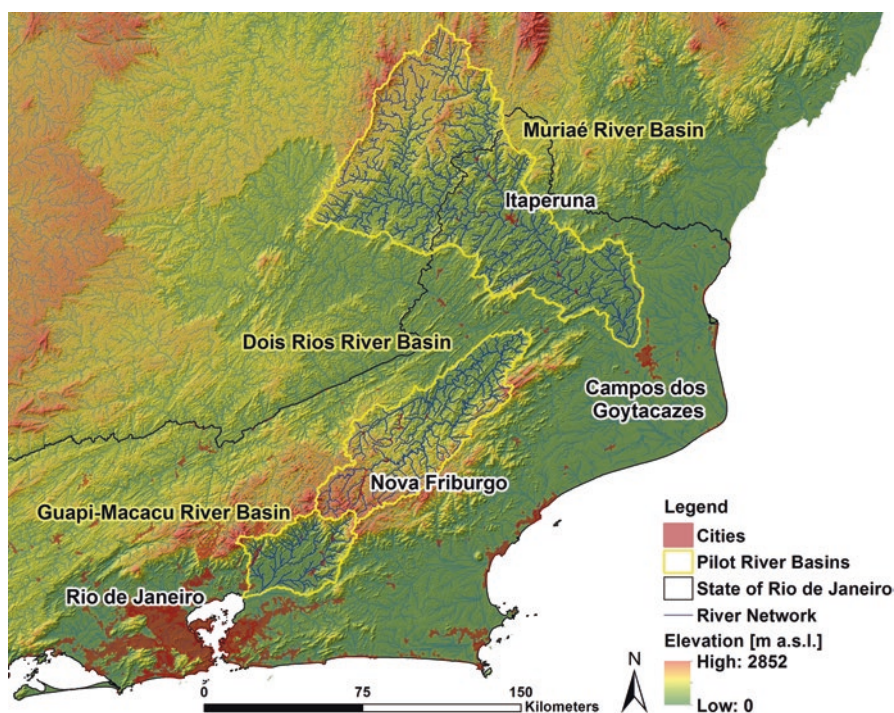

Fig. 17.1 Location of the study area and pilot river basins: GMRB, DRRB, and MRB

influence at the coast (Aw after Köppen and Geiger; Kottek et al. 2006) to a mild temperate, fully humid climate with warm summers in the northeast (Cfb after Köppen and Geiger; Kottek et al. 2006). In the area where the mountain range of the Serra dos Órgãos dominates the weather regimes, there is a more distinct wet and dry season as well as lower temperatures.

2. The second study area – the Dois Rios River basin (DRRB; 3122 km^2), in the northeast of the GMRB – shows similar conditions. The water flows from the Serra dos Órgãos mountain range to the northeast until the Dois Rios River flows into the Paraíba do Sul River. The land use is mainly forest and pasture. Both adjacent river basins have high relief energy, emanating in the Serra dos Órgãos at ca. 2,300 m.a.s.l. to altitudes of just a few m.a.s.l. at the outlets.

3. The Muriaé River basin (MRB) is located in the north of RJ state, with its upstream part in the state of Minas Gerais. With 8,165 km^2, the MRB is the largest of the pilot river basins within this study. It is characterized by a warmer and drier climate compared to the other basins. However, the dominant land use is also forest and pasture, whereby the latter one is more intensively used here than in the other two basins due to high milk production in this area (Zoccal et al. 2006). Geology and soils are more calcareous, which together with the climate and farming causes high degradation, especially on pasture (see Santos et al. 2018; Sattler et al. 2018; Seliger et al. 2018, in this book).

17.2.2 *System Analysis, Data Acquisition, and Data Processing*

Table 17.1 gives an overview of the different types of collected data, which were analyzed and preprocessed for the modeling purpose.

Primary data was collected for the GMRB from 2010 to 2012. The hydrological and meteorological measurements were carried out by Künne and Penedo (Penedo et al. 2011). Soil sampling and physical and chemical soil measurements were conducted by Leipzig University (Nehren et al. 2013; Kirchner 2014). Vegetation studies were also conducted by Leipzig University (Wesenberg and Sattler 2011; Lindner and Sattler 2012; Sattler et al. 2014). As a result of these measurements, the analysis of the leaf area index and root depth could be used for the parameterization of the model.

All time series data were analyzed, tested for homogeneity (e.g., double-mass curve method and in case of errors corrected (see Santos et al. 2018). The spatial data (e.g., soil, land use, geology) were checked for validity and consistency, by using measured physical information compiled out of different sources.

With regard to the modeling process, the data analyzed and processed were either prepared as model input time series or as data for parameterization. Table 17.2 provides an overview of the data preparation, explaining which data was used for what purpose.

Table 17.1 Data collected and used within the study

Data	Responsible organization/person	Resolution and date
Digital elevation model to delineate topographical information (e.g., slope, aspect)	Shuttle radar topography mission (SRTM non-void filled) (Data available from the U.S. Geological Survey 2015)	1 arc-sec, 30 m
Soil maps	Carvalho Filho et al. (2000)	1:250,000
Physical soil information (e.g., texture, bulk density)	Soil Department of Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA 1980), Kirchner (2014)	2010–2012
Land use maps	Serviço Geológico do Brasil – CPRM (Duringer and Shinzato 2000)	1:250,000
Physical vegetation information (e.g., LAI, root depth)	Wesenberg and Sattler (2011), Lindner and Sattler (2012), Sattler et al. (2014), Künne and Penedo (2012)	2010–2012
Geology	Departamento de Geologia da CPRM (Silva and Silva Cunha 2001)	1:500,000
Physical geological information (e.g., type of aquifer, conductivity)	Menezes Raposo de Almeida et al. (2010)	
Discharge data	ANA Agência Nacional de Águas (2015)	Daily (1933–2015)
	Penedo et al. (2011), Künne and Penedo (2012), Künne et al. (2016)	Daily (2010–2012)
Precipitation data	INMET Instituto Nacional de Meteorológia (2015), ANA Agência Nacional de Águas (2015)	Daily (1935–2015)
	Penedo et al. (2011), Künne and Penedo (2012), Künne et al. (2016)	Daily (2010–2012)
Meteorological data (temperature, wind speed, humidity, solar radiation, or sunshine duration)	INMET Instituto Nacional de Meteorológia (2015)	Daily (1931–2015)
	Penedo et al. (2011), Künne and Penedo (2012), Künne et al. (2016)	Daily (2010–2012)

17.2.3 *Ecohydrological Modeling*

This section describes the development and adjustment of the models to the specific conditions of the pilot river basins. Furthermore, the delineation of the spatial model entities and the definition of the parameters for describing soils, geology, and land use are presented. Additionally, a short overview is given on model calibration and validation, followed by a description of the model optimization, sensitivity, and uncertainty analysis.

Table 17.2 Overview of the model parameters needed as well as data and sources used for the reclassification and the final parameterization

Maps state of RJ	Source	Reclassification	Sources for parameterization (physical soil analysis)	Parameters for J2K per each class
Soil map	Carvalho Filho et al. (2000)	Yes. FAO classification used (IUSS Working Group WRB 2006)	Kirchner (2014), (EMBRAPA 1980), Menezes Raposo de Almeida et al. (2010)	Soil depth, field capacity (sum and per dm depth), sum of air capacity, capillary rise
Land use/land cover map	Duringer and Shinzato (2000)	No	Lindner and Sattler (2012), Wesenberg and Sattler (2011), Sattler et al. (2014), Fidalgo et al. (2008), Xavier and Vettorazzi (2003), Freitas et al. (2005), Campoe et al. (2010)	Albedo, stomata resistance for each month of the year, LAI and height of plants every quarter of the year, grade of sealing, root depth
Geology map	Departamento de Geologia da CPRM (Silva and Silva Cunha 2001)	Yes, depending on aquifer conductivity	Menezes Raposo de Almeida et al. (2010)	Storage capacity and conductivity of two components RG1 (weathering belt) and RG2 (base rock)

17.2.3.1 Modeling Software

The software JAMS/J2K was used for the ecohydrological modeling within the studied river basins and their sub-catchments. J2K is a process-oriented, fully distributed ecohydrological model that was designed to simulate hydrological processes on the catchment scale (Krause 2001). J2K is built within the JAMS software, which is an object-oriented modular modeling framework to design custom-tailored models. The modeling framework allows the analysis of data and supports the parametrization as well as the manual and automatic calibration of the models. Moreover, JAMS enables an evaluation of results and sensitivity and uncertainty analyses (Kralisch and Krause 2006). J2K uses the concept of hydrological response units (HRU) – as suggested by Flügel (1996) and Pfennig et al. (2009) – to represent the spatial heterogeneity of the basins. The concept considers topographical, pedo-geological, and land use information as well as a routing scheme incorporating different flow topologies.

17.2.3.2   Model Design and Development

The modular approach of the JAMS framework allows designing custom-tailored models (Kralisch and Fischer 2012). The user can select different simulation components from a component library or use full-fledged sub-models in order to read inputs, simulate processes, and generate outputs, depending on the specific research questions. The extensible JAMS component library provides a plethora of different process simulation routines, for example, to simulate evapotranspiration, soil water processes, or stream routing. The component libraries offer routines to simulate processes in different ways that require varying amounts of input data, e.g., the algorithms after Penman-Monteith (Penman 1948; Monteith 1965) and Hargraves-Samani (Samani 2000) in the case of evapotranspiration.

   With regard to the research questions of this study, the model design allows simulating the following processes: interception, evapotranspiration, infiltration, percolation, runoff generation, and stream routing. Depending on the data availability and in regard to the physical-based approach, the model was designed using specific components and equations. The snow module, which is a standard component of the J2K model, was removed as snow does not play a role within the study area. Since J2K was applied for the first time in the region, other minor adaptations had to be carried out, e.g., for the calculation of the precipitation correction and the calculation of solar radiation. The austral summer also had to be taken into consideration in some components.

17.2.3.3   Parameter Identification

As mentioned before, the J2K model was developed and first tested under temperate climate conditions (Krause 2001). Despite the fact that the model has been used all over the world in tropical as well as low-temperate regions influenced by glaciers, this is the first application in the Mata Atlântica. Hence, the existing parameter libraries of soil classes, land use classes, and geological classes needed to be adapted and updated to describe the ecohydrological conditions of this region. This was done by the analysis of collected primary and secondary data sources.

   The parameterization was done for the entire state based on the maps of geology, soil, and land use/land cover, which were provided by the state environmental agency INEA (Instituto Estadual do Ambiente), from different sources (see Table 17.2).

   For the parameterization of the soil classes, the data that was analyzed by Leipzig University (Kirchner 2014), Embrapa Solos (EMBRAPA 1980), and the Projeto Macacu (Sin Hwa et al. 2010) was used to parameterize all soil classes for the whole RJ and the upper part of the Muriaé river basin located in Minas Gerais (Table 17.2).

17.2.3.4   Model Calibration, Validation, and Sensitivity Analysis

Sensitivity analysis was done with the OPTAS tool, which is part of the JAMS software (Fischer et al. 2009). In doing so, we were able to identify the most sensitive parameters that have a high impact during calibration. In addition, understanding about the river basin systems within the region could be enhanced by studying the parameter sensitivity.

The main differentiation of calibration methods for hydrological models is made between automatic and manual calibration (Boyle et al. 2000). We decided to use a semiautomatic model calibration using both calibration approaches. Hereby, 11 parameters and their specific boundaries were manually selected out of 48 calibration parameters in the model. The selected parameters were calibrated using the multi-objective genetic algorithm NSGA-2 (Deb et al. 2002). Choosing this semiautomatic calibration procedure allowed us to exploit the understanding and representation of ecohydrological processes gained in field surveys and measurements, which played a major role in our study.

17.2.4   Modeling Future Climate Impacts

The selection of the regional climate models for impact assessment was mainly guided by their spatiotemporal resolutions. To simulate flood events or low flow situations, daily input data were needed. Moreover, regional climate models where used to make sure that the regional orography was well represented. The evaluation of different models and platforms resulted in the following six models of the CORDEX (COordinated Regional climate Downscaling Experiment) initiative (Evans 2011) for South America:

  (i) EC-Earth-hist
 (ii) EC-Earth-RCP4.5
(iii) EC-Earth-RCP8.5
(iv) MPI-ESM-hist
 (v) MPI-ESM-RCP4.5
(vi) MPI-ESM-RCP8.5

Each of these models represents a combination of an Earth system model (EC-EARTH, MPI-ESM), a regional model (RCA4), and a development scenario (hist, RCP4.5, RCP8.5). These are in detail:

- EC-Earth: The European Earth system model (EC-Earth) (Hazeleger and Bintanja 2014).
- MPI-ESM: This model was developed by the Max Planck Institute (MPI) for Meteorology in Hamburg, Germany, and consists of different components for simulating dynamics of the atmosphere (ECHAM6), the oceans (MPIOM), land surfaces (JSBACH), and their interactions (Hagemann et al. 2013).

- hist: This hindcast scenario assumes the historic conditions with radiative forcing between the years 1951 and 2005.
- RCP4.5: Representative Concentration Pathways (RCPs) represent an assumed radiative forcing until the year 2100. This scenario assumes a stabilization of radiative forcing by different greenhouse gases at 4.5 W/m^2 (ca. 650 ppm CO2 equivalent) until the year 2100 (Thomson et al. 2011).
- RCP8.5: This RCP scenario assumes an increase of radiative forcing leading to 8.5 W/m^2 (rd.1370 ppm CO2 equivalent) stabilization until the year 2100 (Vuuren et al. 2011).

Both Earth system models were downscaled using the Rossby Centre regional atmospheric model (RCA4), which resulted in a spatial resolution of 0.44°, equivalent to approx. 49 km grid size in the project region. In order to create input data for the J2K model, the grid cells that intersect the catchments plus one additional layer of surrounding cells were selected, which resulted in 22 grid cells. For each of the six models and the selected cells, J2K input datasets for precipitation, temperature (minimum, maximum, and mean), relative humidity, sunshine duration, and wind speed at 2 m above ground were extracted.

Using these climate data as a driver, the catchment's hydrology was simulated with J2K for the following time slices:

(i)   1976–2005 (based on EC-Earth-hist/MPI-ESM-hist)
(ii) 2011–2040 (based on RCP models)
(iii) 2041–2070 (based on RCP models)
(iv) 2071–2100 (based on RCP models)

For each of the resulting 14 time slice/model combinations, the outputs of the hydrological simulation were analyzed in two ways, (i) temporally, by aggregating the spatial outputs of J2K and by analyzing the resulting daily time series, and (ii) spatially, by aggregating the temporal outputs on a quarterly basis and by creating long-yearly averages of the quarterly data.

For the analysis of the daily time series, the software IHA (indicators of hydrologic alteration) (The Nature Conservancy 2009) was used. The software was developed to analyze the impacts of hydrological alterations (e.g., dam constructions), with respect to both short-term and long-term changes. For this study, the simulated streamflow for the historical period was compared to the results of the three future time slices. This comparison was repeated for each of the four RCP-based models.

For each of the 14 time slice/model combinations, overall 67 statistical parameters were calculated with the IHA software based on daily, monthly, and yearly values (e.g., 7-day minimum, 25th/50th/75th percentiles, and extremes). Moreover, by using IHA, the following five flow components of ecological importance – also denoted as environmental flow components (EFCs) – were analyzed: extreme low flows, low flows, high flow pulses, small floods, and large floods. These were in detail:

- *Extreme low flows*: occur during drought periods and restrict water availability. Defined here as all low flow days with a flow value below 10% of daily flows for the related 30-year period.

- *Low flows*: main flow condition, especially during the dry season; the low flow determines water availability within a region. Defined here as all flows below 75% of daily flows for the related 30-year period.
- *High flow pulses*: are related to rainy events or the rain season, where the flow is above low flow levels but not more than bank full. They ensure water availability. Defined here as flows that exceed 75% of daily flows for the assigned 30-year period.
- *Small floods*: The river exceeds and crosses the main channel but is not defined as a large flood. Defined here as an initial high flow pulse with a peak flow greater than a 2-year return interval within the related 30-year period.
- *Large floods*: occur more rarely but with higher impacts by destroying habitats and changing river morphology to a greater or lesser extent. Besides negative anthropogenic impacts, large floods also bring nutrients to the flood plain and surrounding area and can recharge groundwater storage. However, within the study region, floods show a destructive character, demolishing lives as well as urban and arable land, and hence are connected to major expenses for human communities. They are defined here as an initial high flow pulse with a peak flow greater than an event with a 10-year return interval within the related 30-year period.

In addition to the ECF analysis, different statistical analyses were carried out, both spatially and temporally, e.g., the distribution of all parameters modeled for all time slices or the climatic water balance (CWB), which takes precipitation and actual evapotranspiration into account. The rationale is to highlight changes of future water availability for a basin.

17.3   Findings

Within this section, the results of this study will be presented in the same order as presented within the Data and Methods section (Sect. 17.2).

17.3.1   *System Understanding/Data Acquisition and Processing*

Throughout this study, more than 200 time series and more than 80 geo data sets and 200 soil samples from RJ were collected from different project partners. The data was processed, verified and corrected, and made available within the river basin information system (INTECRAL-RBIS). Using the web-based user interfaces of INTECRAL-RBIS, all required J2K input data were downloaded for the study regions, in the case of time series data already formatted according to the J2K requirements. In order to delineate the required spatial modeling units (HRUs), spatial input data on elevation, soil, geology, and land use were processed using the

web-based *HRUweb* geodata processing software. The parameterization was done for whole RJ and the upper part of MRB in order to ensure a fast and transparent model setup in any other basin within the region.

17.3.2   Ecohydrological Modeling

The J2K model was applied in three study areas, namely, DRRB, GMRB, and MRB (see Sect. 17.2.1). However, only DRRB will be used to exemplify the modeling results. Figure 17.2 shows the results of the simulated and observed runoff at gauge Dois Rios and the precipitation for the hydrological years 2009 until 2012. The comparison between measured and simulated hydrographs illustrates that the model simulates the hydrological dynamic very well. This is especially true for the fast response to precipitation events. Moreover, the low flows during the dry season are represented with high accuracy. This is reflected in the statistical efficiency criteria used to evaluate model performance. Table 17.3 shows the efficiency criteria chosen and the rationale behind their selection. The base flow was simulated very well, which is displayed by the logarithmic Nash-Sutcliffe efficiency of 0.79. Looking at the graph, it becomes evident that peak flows were predicted precisely, which is also represented by the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970) of 0.78 as well as by the relative volume error (pBIAS), which shows that the model overpredicts discharge by 5.9%. The Kling-Gupta efficiency (KGE; Gupta et al. 2009) of 0.88 emphasizes a very good match between simulated and observed runoff with regard to correlation, bias, and variability. However, both the visual data plot and the statistical evaluation show that the model was able to represent the hydrological dynamic and processes within the basin well.
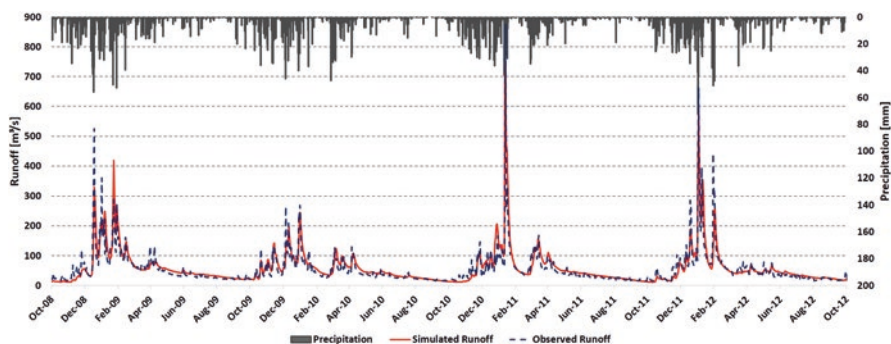

Fig. 17.2 Observed and simulated runoff at gauge Dois Rios

Table 17.3 Efficiency criteria used to evaluate model performance of the model (Gupta et al. 2009). Values here for the J2K model for DRRB and hydrological years 2009–2012

Efficiency criteria	Reason for selection	Range	Value
Nash-Sutcliffe efficiency (NSE)	Multi-objective function, strong focus on simulation of peak flows	$(-\infty, 1)$	0.78
Logarithmic Nash-Sutcliffe efficiency (LogNSE)	Like NSE, but logarithm focuses on representation of simulation of base flow	$(-\infty, 1)$	0.79
Kling-Gupta efficiency (KGE)	Aggregated multi-objective function, representing bias, correlation, and flow variability	$(-\infty, 1)$	0.88
Relative volume error (pBias)	Representing overall under- or overestimation	$(-\infty, \infty)$	5.9%

17.3.3   Modeling Future Climate Impacts

Within the DRRB, the EC-Earth-based models predict an increase of the mean temperature by 1.8 °C until the end of the century in scenario RCP4.5 and by 3.1 °C in scenario RCP8.5 (Fig. 17.2). These differences are less pronounced for the scenario RCP4.5 but show the same pattern. To highlight the extreme development scenarios, we focus on the RCP8.5 emission scenario, the EC-Earth model, and the time slice from 2071 to 2100 (Fig. 17.3).

Besides the overall increasing temperature, precipitation shows a more diverse picture. Considering scenario RCP8.5, Fig. 17.4 emphasizes that until the year 2100, less rainfall (−15%) will occur during the dry season, here represented by the quarter September, October, and November (SON), and more rain (6%) will occur during the rainy season, represented by the quarter December, January, and February (DJF). However, the analysis of the time series shows that the increase of rain until the year 2100 is mainly driven by extreme events within the rainy season.

The changes in temperature and rainfall have a direct effect on the hydrological dynamics (including extreme events) and water availability in the region. Figure 17.5 shows the modeled quarterly sum of total runoff of each HRU within DRRB for SON, between 1976–2005 (EC-Earth-hist) and 2071–2100 (EC-Earth-RCP8.5 scenario). A comparison of these two time slices of SON clearly indicates that less runoff is predicted for the future scenario (a 34% reduction for the entire basin). As expected, the actual evapotranspiration shows an increase of 30% resulting in less available water. With our spatially distributed simulation of the total runoff, we identified hot spot areas with pronounced changes (Fig. 17.5). For instance, the scenarios show that areas with a total runoff of less than 100 mm will increase – not only close to the outlet, but also in the headwater areas where these patterns rarely occurred in historic times.

Actual evapotranspiration is predicted to increase throughout the whole year until the end of the century, whereby the overall rise is higher in SON (15%) than in DJF (6%).
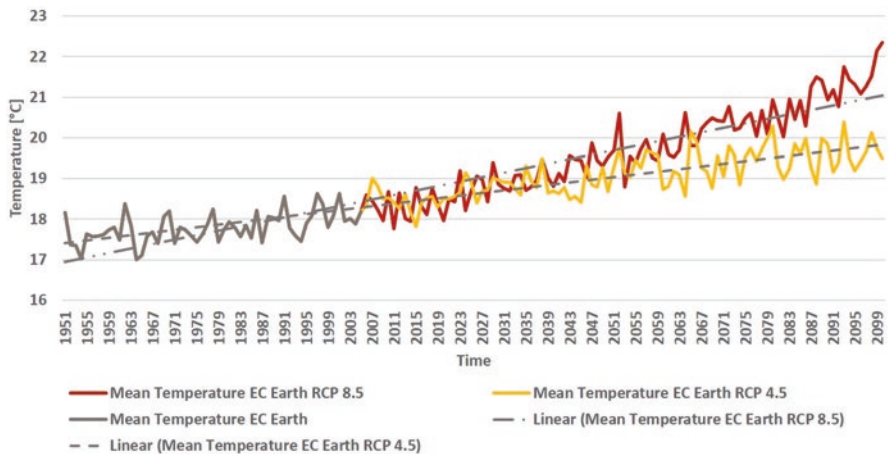
Fig. 17.3 Mean temperature derived from EC-Earth historical data and future climate scenarios RCP4.5 and RCP8.5 for the DRRB
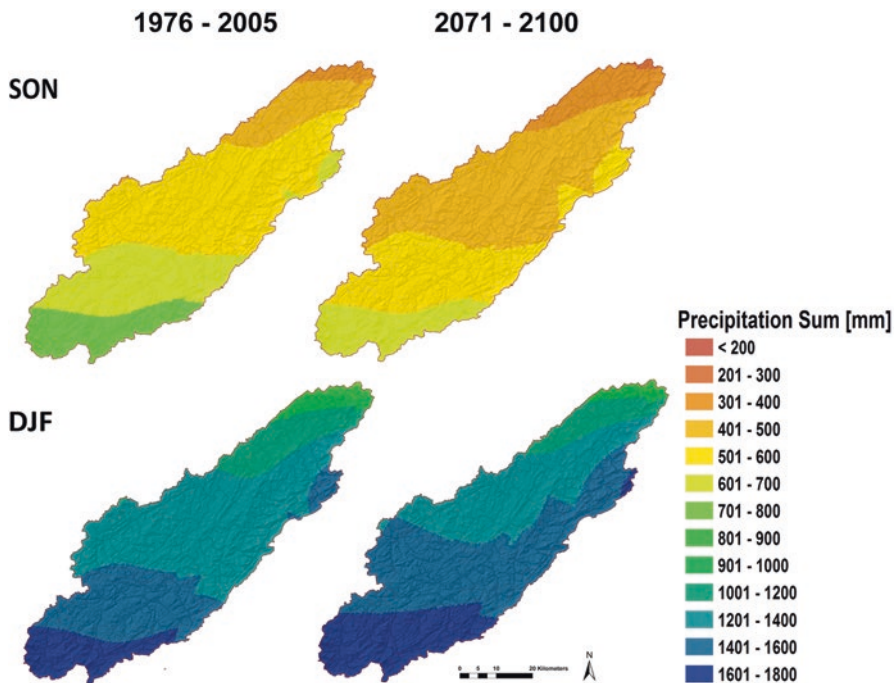

Fig. 17.4 Spatial distribution of mean sum of quarterly precipitation for DRRB between historic data and the time slice 2071–2100 of EC-Earth-RCP8.5 scenario
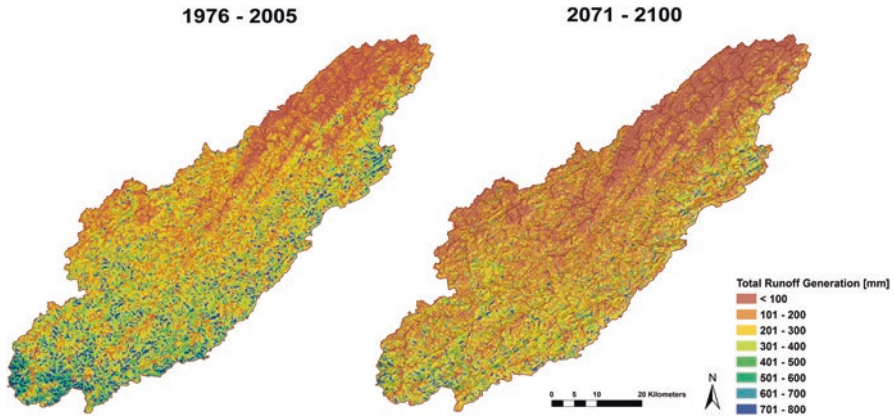
Fig. 17.5 Spatial distribution of mean sum of total runoff per HRU in SON between historic data (1976–2005) based on EC-Earth-hist and the time slice 2071–2100 based on EC-Earth-RCP8.5
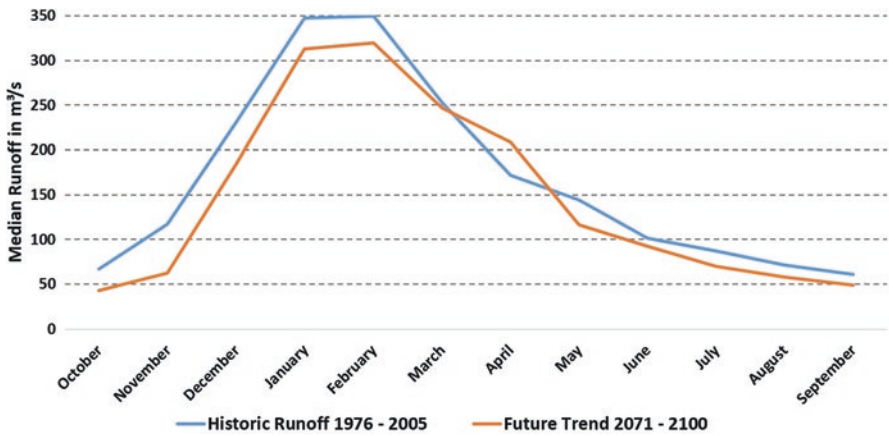

Fig. 17.6 Median runoff for the 30-year period of historic data based on EC-Earth-hist and the time slice 2071–2100 based on EC-Earth-RCP8.5

The hydrological predictions show less water availability in the future, which is also indicated by a lower median value throughout almost the entire year (cf. Fig. 17.6). However, the number and intensity of single flood events increase considerably, especially in the time slice 2071–2100 (cf. Fig. 17.7). Figure 17.7 shows that especially large floods, defined here as peak flow greater than an event with a 10-year return interval, will increase in number and intensity. The J2K model predicts for the DRRB that 0.6% of all daily flows will be large floods (based on the EC-Earth-hist model), while it simulates an enormous increase (3.4% of total flow as large floods) for the EC-Earth-RCP8.5 model (time slice 2071–2100).
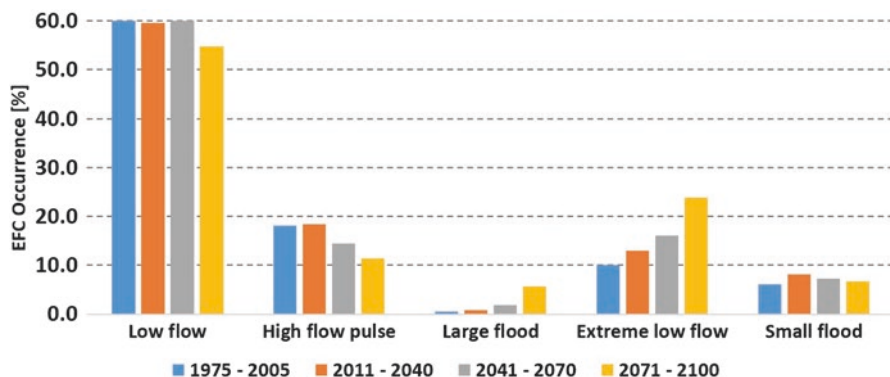
Fig. 17.7 Occurrence of environmental flow components (EFCs) for the different time slices as simulated with J2K based on the EC-Earth-hist and EC-Earth-RCP8.5 scenarios. The definition of the EFCs is described in Sect. 17.2.4

In contrast, low flows would decrease by 11%, but also high flow pulses are projected to decrease by around 7% (while small floods will increase by 0.4%). These projections are all for the time slice 2071–2100 and based on EC-Earth-RCP8.5. However, extreme low flows are predicted to show an increase of 14% until the end of the century (cf. Fig. 17.7).

17.4 Discussion and Conclusion

Sound river basin management requires an understanding of the impacts of future changes on dominant hydrological processes and their dynamics, e.g., with regard to climate and land use changes. Ecohydrological models as applied in the presented study are valuable tools to address this problem. Events like the water crises in the southeast of Brazil during 2014 and 2015 illustrate the need for integrated river basin management, which is based on a thorough social-ecological system understanding that takes the specific conditions of the region into account. Besides human impact of, e.g., agricultural, industrial, and service-oriented water use, this management has to consider how future climate or changing land use can impact water availability in general and hydrological dynamics in particular.

Our study of future climate impacts on water resources for representative basins within RJ reveals that less water will be available in the future. While our models projected this effect throughout the entire year, it was especially pronounced during the dry season. As an example, our models simulated 34% less runoff for the dry season within the time period 2071–2100 (EC-Earth-RCP8.5 scenario). On the other hand, extreme precipitation events will increase during the wet season, which will lead to a higher intensity and frequency of flood events. An analysis of the

model results using the indicators of hydrologic alteration (IHA) showed that the number of days with occurring floods will be more than five times higher for the mentioned scenario. In order to prevent severe socioeconomic damages, counteractions therefore need to be established sooner than later.

Modeling is always linked to uncertainties that stem from data, general model assumptions, and the underlying process representations. Every step of model development, from the observation of data to the generation and linkage of complex models, comes with its own uncertainties, which can accumulate throughout the process. Different methods were applied in the various work steps to minimize errors, e.g., by using homogeneity tests on observed data (see Santos et al. 2018 in this book). Furthermore, selection of model parameters focused both on model performance criteria and overall robustness and transferability (Künne et al. 2016).

This chapter presents only the results of the ecohydrological modeling and climate impact assessment for the DRRB. However, ecohydrological models were also applied in two other study areas, i.e., in GMRB and MRB. Additionally, the calibrated and validated models were applied in different sub-basins within the region. The results could not all be presented here but showed similar or even better performances with regard to statistics as well as visual model interpretation. The model achieved best results for the headwater areas, which are characterized by steep slopes and less soil depth. The three river basins (GMRB, DRRB, and MRB) all feature a great variety in elevation and relief energy and show differences in soil types and land use. Global model parameters, which were adapted during the calibration process, make it hard to account for these differences. However, our overall objective was the development of a transferable ecohydrological modeling platform that can be used for change impact assessment in the entire rural RJ region. The results show that we met this objective, which can be seen in the following achievements:

 (i) The improvement of the understanding of the relevant processes and their interactions
 (ii) The design of computer models to analyze and predict integrated ecohydrological systems
(iii) The evaluation of future development scenarios and the quantification of their impacts on hydrology

The work and results presented in this chapter were made available for all project partners and stakeholders and can be used for knowledge-based decision-making in river basin management of the pilot river basins and all their sub-basins. Moreover, the solid data basis and parameter definition for all types of hydro-geology, soil, and land use occurring in RJ and the Muriaé river basin together with the flexible JAMS/J2K modeling platform build the basis for ecohydrological modeling studies in the future. Further, the presented methods to assess climate impacts can be transferred and reproduced in other regions and can thus build the basis for a science-based search for related adaptation measures.

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