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RESEARCH ARTICLE

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The effect of stream shading on the inflow characteristics in a downstream reservoir

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Abstract

In thermally stratified reservoirs, inflows form density currents according to the interplay between inflow temperature and reservoir stratification. The temperature of inflowing water is affected by catchment properties, including shading by riparian vegetation. We hypothesize that the degree of shading in the catchment can affect the inflow dynamics in downstream reservoirs by changing inflow temperature and consequently the nature of the density current. We test it for a subtropical drinking water reservoir by combining catchment-scale hydrological and stream temperature modeling with observations of reservoir stratification. We analyze the formation of density currents, defined as under, inter and overflow, for scenarios with contrasting shading conditions in the catchment. Inflow temperatures were simulated with the distributed water-balance model LARSIM-WT, which integrates heat-balance and water temperature. River temperature measurements and simulations are in good agreement with a RMSE of 0.58°C. In simulations using the present state of shading, underflows are the most frequent flow path, 63% of the annual period. During the remaining time, river intrusion form interflows. In a scenario without stream shading, average inflow temperature increased by 2.2°C. Thus, interflows were the most frequent flow path (51%), followed by underflows (34%) and overflows (15%). With this change, we would expect a degradation of reservoir water quality, as overflows promote longer periods of anoxia and nutrient loads would be delivered to the photic zone, a potential trigger for algae blooms. This study revealed a potentially important, yet unexplored aspect of catchment management for controlling reservoir water quality.

KEYWORDS
density currents, reservoirs, riparian vegetation, stream shading, water quality

1 | INTRODUCTION

During the last two decades, dam construction has been increasing and by considering the ongoing construction and planning of new dams this trend is expected to continue (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2014). The current boom of dam construction documented by Zarfl et al. (2014) was based on estimates of hydropower dams only, additional dams are constructed for flood control and water storage for drinking water and irrigation (Grill et al., 2019; Lehner et al., 2011). Dams disrupt natural hydrological, geological and biogeochemical cycles (Friedl & Wüest, 2002; Poff, Olden, Merritt, & Pepin, 2007; Vörösmarty et al., 2003). The consequences of river damming for water quality and biodiversity have been intensively assessed for downstream river reaches and river basins (Bunn & Arthington, 2002; Vörösmarty et al., 2010), but also water quality in the impounded water bodies is of great concern, as it potentially jeopardizes their economic and societal values.

The efficient trapping of nutrients, including phosphorous and nitrogen (Akbarzadeh, Maavara, Slowinski, & Van Cappellen, 2019; Maavara et al., 2015), in combination with prolonged water residence time and the potential development of thermal stratification, promote eutrophication and harmful algae blooms in the impoundments (Winton, Calamita, & Wehrli, 2019). Nutrient enrichment is the primary cause for eutrophication and the occurrence of harmful algae blooms, which nowadays are the main problems related to water quality (Paerl & Otten, 2013; Schindler, 2012; Smith & Schindler, 2009). The possible consequences are the killing of fish due to the depletion of oxygen or the release of toxins from algae and sediments, as well as increased concentration of suspended and dissolved substances that affect odor and color. Such degradation of water quality increases treatment costs (Dodds et al., 2009; Pretty et al., 2003; Walker Jr, 1983).

In addition to climatic and geographic boundary conditions, reservoir water quality is controlled by the inflowing nutrient load and reservoir hydrodynamics. In stratified reservoirs, inflows form density currents that are classified according to their depth of intrusion: underflows follow the reservoir bottom, overflows stay at the reservoir surface, and interflows enter at intermediate depths (Wetzel, 2001). The type of density current depends on inflow temperature and reservoir stratification and eventually controls the distribution of the nutrient load in the reservoir and its availability for algae growth (Ayala, Cortés, Fleenor, & Rueda, 2014; Rueda, Fleenor, & de Vicente, 2007).

Water temperature of the inflowing streams depends on meteorological and hydrological conditions (Caissie, 2006; B. W. Webb, Hannah, Moore, Brown, & Nobilis, 2008). However, stream temperature is also affected by catchment properties, including shading by riparian vegetation. In particular, stream water temperature has been observed to increase following deforestation, or to decrease in response to tree growth in many studies (see reviews in Beschta, Bilby, Brown, Holtby, & Hofstra, 1987; D. R. Moore, Spittlehouse, & Story, 2005). More recently, the impact of riparian vegetation on stream water temperature has been studied using different empirical and modeling approaches. These studies showed, that the magnitude of temperature reduction due to riparian vegetation depends on many different aspects, including vegetation density, vegetation height, stream width, stream orientation, contribution of net shortwave radiation to the overall energy budget, geographical latitude, solar angle and many others (e.g., Dugdale, Malcolm, Kantola, & Hannah, 2018; Garner, Malcolm, Sadler, & Hannah, 2014, 2017; Garner, Malcolm, Sadler, Millar, & Hannah, 2015; Kalny et al., 2017; D. R. Moore et al., 2005; R. Moore, Leach, & Knudson, 2014; Regenauer, Haag, & Aigner, 2019; Trimmel et al., 2018). In general, the effect of dense riparian vegetation is most pronounced during times of high water temperature, when the energy budget is dominated by short wave radiation (e.g., Garner et al., 2014; Hannah, Malcolm, Soulsby, & Youngson, 2008). It is thus well established that riparian vegetation helps to reduce maximum stream water temperatures and thermal variability. Consequently, shading is often considered in catchment management and stream restoration efforts and is among the three most important environmental state variables in assessments of stream restoration success (Feld et al., 2011).

The effect of stream shading on inflow dynamics in downstream reservoirs has not been studied. We hypothesize that the degree of shading in the catchment can affect the inflow dynamics in downstream reservoirs by changing inflow temperature and consequently the nature of the density current. As riparian stream shading is closely related to land use in the catchment, this mechanism would constitute an unexplored influence of catchment management on reservoir water quality. Here we test this hypothesis for a tropical drinking water reservoir. We combine catchment-scale hydrological and stream temperature modeling with observations of reservoir stratification and analyze the formation of density currents for scenarios with contrasting shading conditions in the catchment. We further discuss the potential implications of stream shading for reservoir water quality and the broader relevance of the studied process.

2 | METHODS

2.1 | Study site

Passaúna reservoir is a drinking water reservoir in a tropical to subtropical region in south Brazil (latitude: $-25°30'$ and longitude: $-49°22'$). It produces around 1.8 $m^3\ s^{-1}$ of drinking water for parts of the city of Curitiba and three neighboring cities (SANEPAR, 2013). The reservoir has a maximum depth of 15 m, a surface area of 9 km^2 and an approximate volume of $60 \times 10^6\ m^3$ (Carneiro, Kelderman, & Irvine, 2016). The catchment of the reservoir covers an area of 143 km^2 (Figure 1). Mean air temperature within the catchment was approximately 18.7°C and mean yearly precipitation approximately 1,650 mm (years 2009 through 2018). A relatively high proportion of the catchment (44% for catchment of gauge Campo Largo) was covered by broad-leaved mainly evergreen forest (Figure 1). Passaúna River is the dominant inflow to the reservoir. It drains an area of approx. 100 km^2 and delivers around 75% of total annual inflow to the reservoir (Carneiro et al., 2016). Simulated mean annual discharge at gauge Campo Largo (84 km^2) reached approx. 2 $m^3\ s^{-1}$ (2010 through 2018).

2.2 | Observational data

The investigation period of the present study covers 1 year from March 2018 through February 2019. During that period, water

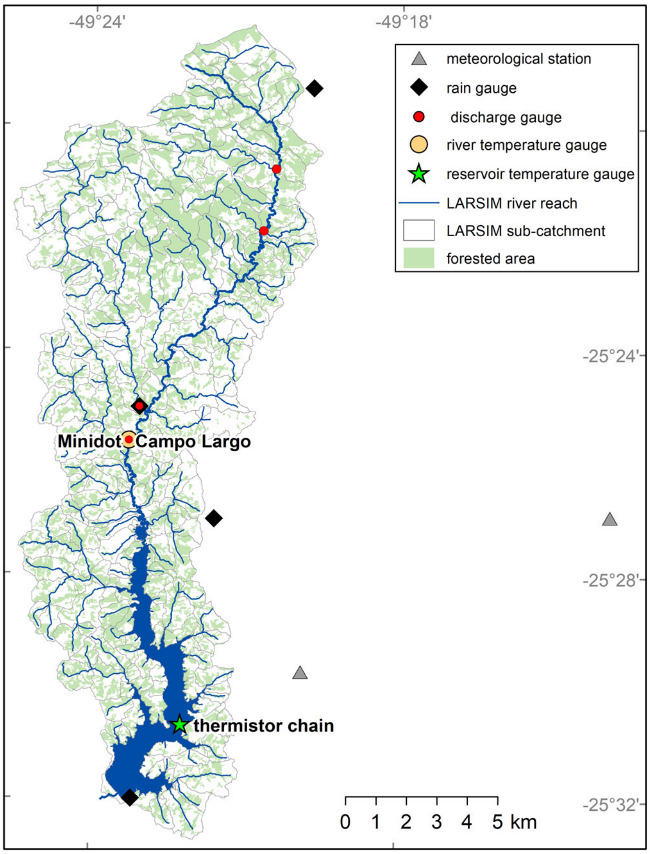

FIGURE 1 Map of the catchment of Passaúna reservoir, including all stream segments and sub-catchments resolved by the model (LARSIM). The locations of water temperature gauges, discharge gauges, rain gauges and meteorological stations used in this study are marked by symbols (see legend) [Color figure can be viewed at wileyonlinelibrary.com]

temperature was monitored in the Passaúna River and reservoir. At Passaúna River, water temperature was measured approximately 3 km upstream of the reservoir inflow near the gauging station Campo Largo using a temperature sensor (miniDOT, Precision Measurement Engineering Inc.) with a temporal resolution of 15 min, an accuracy of ±0.1°C and a resolution of 0.01°C (Figure 1). In the reservoir, a vertical thermistor chain with 11 temperature sensors (Minilog-II-T, Vemco) was deployed close to the intake station of the waterworks (Figure 1), at a mean water depth of 12 m. The chain was fixed at the bottom with the first logger being 1 m above the bed and all remaining sensors were arranged with a fixed vertical spacing of 1 m. The sampling interval was 1 min, precision and accuracy of the sensors was ±0.1°C and of 0.01°C, respectively.

Additional data for modeling discharge and river water temperature was provided by the Federal University of Paraná (UFPR). Measurements of mean daily discharge were available for four gauges within the catchment (Figure 1). These discharge data were used to calibrate and validate the water balance model over a period of several years (see below; Krumm, Haag, & Wolf, 2019). To simulate discharge and river water temperature during the period of investigation (March 2018 through February 2019) we used daily precipitation from four rain gauges within the catchment along with additional measurements of air temperature, global radiation, humidity and wind speed from two meteorological stations west of the catchment (Figure 1).

2.3 | Integrated water balance and stream water temperature modeling

2.3.1 | Model overview

River discharge and stream water temperature were modeled using LARSIM-WT (Large Area Runoff SIMulation Model – Water Temperature – Haag & Luce, 2008). LARSIM is a process-oriented and spatially distributed water balance model, which simulates all major aspects of the terrestrial water cycle (LEG, 2019). LARSIM also includes an optional water temperature module (WT), which simulates water temperature throughout the complete river network on a physical basis (Haag & Luce, 2008).

Heat transport within the river network was modeled using the one-dimensional advection-dispersion equation. The local heat balance, that is, the source-sink term in the advection-dispersion equation, accounts for heat exchange with the atmosphere and at the river bed:

$$\frac{dWT}{dt} = \frac{R_S + R_L + H_S + H_L + H_{bed}}{cp_S \rho_w h} \tag{1}$$

with WT denoting water temperature (°C), t time (s), cp_W the specific heat capacity of water (J kg^{-1}°C^{-1}), ρ_W water density (kg m^{-3}), h average water depth of the river reach (m), R_S net shortwave radiation (W m^{-2}), R_L net longwave radiation (W m^{-2}), H_S turbulent flux of sensible heat (W m^{-2}), H_L turbulent flux of latent heat (W m^{-2}) and H_{bed} the conductive heat flux at the riverbed (W m^{-2}).

In general, the parametrization of the heat fluxes follows the approach of Sinokrot and Stefan (1993) by using relationships, which were originally derived for open water bodies. Applying these open water body formulae to small rivers with riparian vegetation is a simplification. Nonetheless, this simplified approach is well established and validated in the scientific literature on river water temperature modeling and it is commonly used to evaluate the effect of riparian vegetation on river water temperature (e.g., Dugdale, Hannah, & Malcolm, 2017; Garner et al., 2017; Haag & Luce, 2008; Sinokrot & Stefan, 1993; Trimmel et al., 2018). All terms of the heat balance and their parametrization in LARSIM-WT are described in detail in Haag and Luce (2008). For that reason, we only briefly describe the fluxes, which are influenced by riparian vegetation in the following. Net shortwave radiation R_S at the water surface was calculated from measured incoming shortwave radiation R_{glob} (W m^{-2}) and the albedo of the water surface. For the present study, albedo was assumed to be constant at a value of 0.06. To account for shading by riparian vegetation, a shading factor f_{shade} is used, where $f_{shade} = 0$ corresponds to no shading (i.e., a sky view factor of 1) and $f_{shade} = 1$ for complete shading (i.e., a sky view factor of 0):

$$R_S = (1 - f_{shade})(1 - albedo)R_{glob} \quad (2)$$

The turbulent fluxes of latent heat H_L and sensible heat H_s were simulated with an aerodynamic approach:

$$H_L = -\rho_W L K_L (e_{sat,WT} - e_{air}) \quad (3)$$

$$H_s = -\rho_W L K_L \gamma \frac{P}{1013}(WT - T_{air}) \quad (4)$$

with L denoting the latent heat of vaporization (J kg^{-1}), $e_{sat,Wt}$ the saturation vapor pressure (hPa) at the water surface with temperature WT, e_{air} the actual measured vapor pressure in the air (hPa), γ the psychometric constant at normal pressure (0.655 hPa °C^{-1}), P the measured atmospheric pressure (hPa) and T_{air} the measured air temperature (°C). The aerodynamic coefficient for turbulent exchange of water vapor K_L (m s^{-1} hPa^{-1}) was derived as a function of measured wind speed v_{wind} (m s^{-1}) by the approach of Rimsha and Donschemko (1958), which produces realistic results over a wide range of environmental conditions. Within this formula, we accounted for the effect of wind sheltering by riparian vegetation with a wind shield factor f_{wind}, where $f_{wind} = 0$ corresponds to no wind sheltering and $f_{wind} = 1$ corresponds complete wind sheltering:

$$K_L = \frac{0.211 + 0.103 v_{wind}(1 - f_{wind})}{86.4 \times 10^6} \quad (5)$$

Following commonly applied models in stream water temperature modeling (e.g., Bogan, Mohseni, & Stefan, 2003; Bustillo, Moatar, Ducharne, Thiéry, & Poirel, 2014; Sinokrot & Stefan, 1993), we neglected the possible minor effect of stream shading on longwave radiation in the present study. Numerical analysis by Regenauer et al. (2019) demonstrated that this effect is much less important than the shading of shortwave radiation and the wind sheltering especially for situations with high shortwave radiation and high air temperatures.

2.4 | Application to the Passaúna catchment

In LARSIM-WT, the catchment of Passaúna reservoir was represented by sub-catchments and their corresponding river reaches (Figure 1). The sub-catchments and corresponding river reaches were delineated based on a Digital Elevation Model and a digital river dataset. The model was forced by measured data from nearby rain gauges and meteorological stations at daily resolution, which were spatially interpolated within the model. The discharge model was calibrated using measured time series of four discharge gauges (Figure 1). Simulated discharge was in good agreement with observations yielding Nash Sutcliffe efficiencies of 0.77 at gauge Campo Largo (Krumm et al., 2019) (Figure 2).

Forests and riparian vegetation within Passaúna catchment is mainly made up by broad-leaved mostly evergreen trees, resulting in an almost constant mean leaf area index throughout the year. Therefore, with respect to river shading, we did not have to take into account seasonal changes of the leaf area index of riparian vegetation. Moreover, almost all river reaches in the Passaúna catchment were less than approximately 5 m wide. With respect to river shading, we thus assumed that overhanging canopies of typical riparian trees on both banks may cover the river width completely. Consequently, for dense riparian vegetation we assumed a constant sky view factor that is uniformly distributed throughout the complete hemisphere above the river surface. Thus, we did not take into account additional influencing factors for estimating the shading factor f_{shade}, such as height of trees, width of river reaches, solar angle, stream orientation or the proportion of direct and diffuse global radiation (DeWalle, 2008; Garner et al., 2017; R. Moore et al., 2014; Regenauer et al., 2019). Even for river reaches completely covered by dense riparian trees, still a minor part of the shortwave radiation reaches the water surface. Based on literature data we assumed that approximately 15% of R_{glob} reach the water surface when a river reach was completely covered by dense riparian trees (e.g., Garner et al., 2017; Regenauer et al., 2019; Trimmel et al., 2018). Thus, complete shading of a river reach by riparian vegetation was simulated with $f_{shade} = 0.85$. Literature data also indicate that dense riparian vegetation reduces wind speed to approximately 60% of standard measurements, and that shading and wind sheltering are closely correlated. These assumptions are also corroborated by a different study, in which we simulated long-term river water temperature for the complete river network of the federal state of Baden-Württemberg in Germany (approximately 36.000 km^2). Optimizing and validating simulation results at 200 measurement locations indicated that water temperatures of narrow rivers under dense forest vegetation are simulated best by assuming $f_{shade} = 0.85$ and $f_{wind} = 0.4$ (Haag, 2018). Thus, also in the present study completely shaded river reaches were modeled with $f_{shade} = 0.85$ and $f_{wind} = 0.4$, whereas no shading was parameterized by $f_{shade} = 0.0$ and $f_{wind} = 0.0$. For situations between maximum shading and wind sheltering on the one hand and no shading and wind sheltering on the other hand, f_{shade} and f_{wind} values were interpolated linearly (e.g., Caissie, 2006; Regenauer et al., 2019; Sinokrot & Stefan, 1993).

Exact values of the present state of stream shading along the river reaches were not available, since land use data were not accurate enough to account for small strips of riparian vegetation along the rivers and precise ground mapping of riparian vegetation was not existent. Therefore, we used the proportion of forest within each sub-catchment as a proxy for the spatial distribution of the proportion of riparian vegetation. We then introduced a factor to multiply the relative proportion of forest within each sub-catchment to get the relative proportion of riparian vegetation of the river reaches. We optimized this factor to fit the measured stream water temperature with the model, but did not allow f_{shade} to exceed a maximum value of 0.85 in any river reach. Within our approach, we thus assumed that the actual proportion of riparian vegetation was proportional to the proportion of forest within the sub-catchments. We obtained a mean factor of 1.6. Based on observations in the field, this factor seemed reasonable,

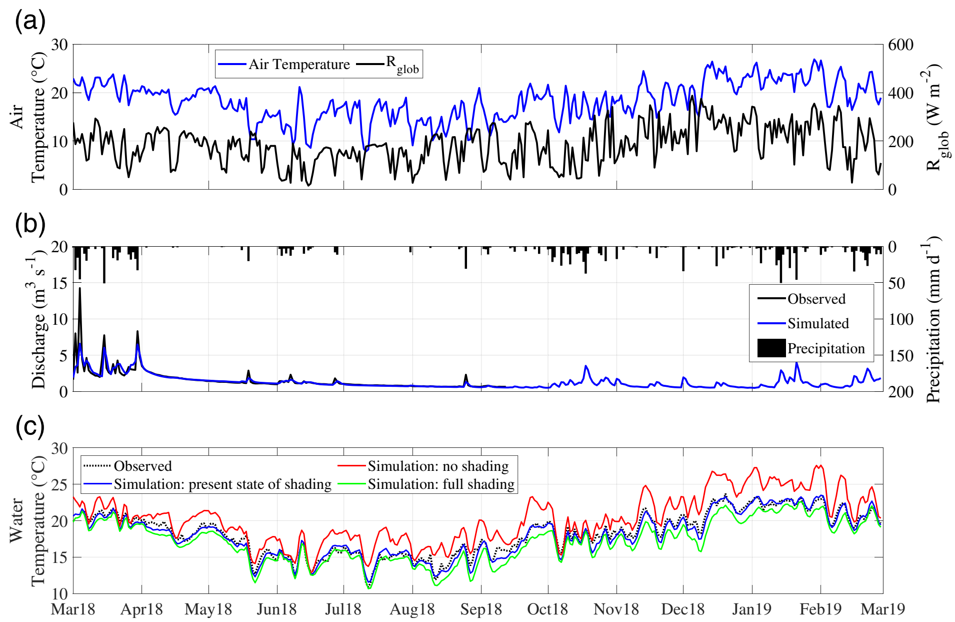

FIGURE 2 (a) Spatial averages of observed air temperature and incoming shortwave radiation R_{glob} within the catchment of gauge Campo Largo in a daily resolution. (b) Observed precipitation along with measured and simulated hydrographs of the Passaúna River at gauge Campo Largo. (c) Time series of observed (dotted black line) and simulated (solid lines) water temperature in the Passaúna River at the temperature gauge (site Minidot). The black dashed line is the observed temperature, blue solid line shows water temperature simulated by the LARSIM-WT model for the present state of shading. The red and green lines show the simulation results for scenarios with no shading and full shading, respectively. All data are shown as daily mean values [Color figure can be viewed at wileyonlinelibrary.com]

since there were many riparian vegetation strips outside forested areas, which increased the first estimate of riparian shading. The optimized factor yielded degrees of shading ranging from 55% to 85% (i.e., f_{shade} varied between 0.55 and 0.85), for the present state of stream shading. The wind shield factor was assumed to vary linearly with the shading factor, as described above. Thus, f_{wind} varied between 0.26 and 0.40.

To analyze the potential effect of stream shading on river water temperatures and inflow dynamics into the reservoir, we defined two scenarios: "full shading" and "no shading." In the full shading scenario for all river reaches we used $f_{shade} = 0.85$ and $f_{wind} = 0.40$. In the no shading scenario, both parameters were fixed at zero for all river reaches.

2.4.1 | Classification of reservoir inflow dynamics

The inflow regime of the river into the reservoir depends on the difference in water density between river water and the seasonally stratified water in the reservoir. Water samples from the analyzed period had maximum total solid concentration of 0.16 g l^{-1} (Oliveira et al., 2019) and the density of the river and reservoir water was mainly controlled by the water temperature.

The intrusion depth of density currents formed at the reservoir entrance was assessed by the difference between the temperature of the inflowing river water and the temperatures observed at the reservoir surface and bottom. The inflow was considered as an overflow, where the river water floats on top of the reservoir, when the temperature of the Passaúna River was higher than the measured surface temperature in the reservoir. When the inflow temperature was lower than the temperature measured close to the reservoir bed, the inflow was classified as underflow, where the river flows along the reservoir bottom. For all other periods, the inflow was considered as interflow, similar to the analysis made by Ishikawa, Bleninger, and Lorke (2021) – accepted at Inland Waters. This analysis was done based on daily mean temperatures.

3 | RESULTS

3.1 | Meteorological conditions and river discharge

During the study period (March 2018–February 2019) average air temperature was 18.3 ± 3.9°C (mean ± *SD*), which was about 0.5°C warmer than the long-term annual average. Air temperature varied seasonally with mean values of 15.1 ± 3.1°C during winter (June to September 2018) and 21.9 ± 2.5°C in summer (March 2018 and December 2018 to February 2019). The average of mean daily shortwave radiation R_{glob} was 184 ± 80 W m^{-2} during the entire year, which was about 17 W m^{-2} more than the long-term average. It also varied seasonally with a winter average of 146 ± 67 W m^{-2} and a summer average of 225 ± 81 W m^{-2} (Figure 2a).

Total precipitation was approximately 1,400 mm for the entire year, which is about 15% below the long-term average of

1,650 mm year^{-1}. The period of investigation started with the relatively wet month of March 2018, followed by a long and extremely dry period from April through September 2018 and it finished with a typical period from October 2018 through February 2019 (Figure 2b).

Discharge of the Passaúna River was successfully calibrated for the 4 year period 2010 through 2013, yielding Nash Sutcliffe efficiencies of 0.77 (Krumm et al., 2019). Based on the simulation results the mean discharge at gauge Campo Largo was 1.4 m^3 s^{-1} during the period of investigation, which is considerably lower than the long-term average of 2 m^3 s^{-1}. The seasonal variation of discharge followed the variation of precipitation: discharge was highest in March 2018. During the following dry season, it gradually dropped to about 0.5 m^3 s^{-1} in September 2018. During the summer 2018/2019 there were some minor peaks, but discharge also frequently dropped to low flow conditions especially, between mid-November and mid-January (Figure 2b). Simulated discharge agreed mostly well with observations at the gauge Campo Largo (measurements were only available until mid-September 2018). Although the major discharge peak in March 2018 was not reproduced well by the model, the minor peaks and in particular, the low flow were simulated very well (Figure 2b).

3.2 | Inflow temperature

Observed river water temperature near the reservoir inflow (location Minidot in Figure 1) varied between 15.3 ± 1.7°C in winter and 21.3 ± 1.2°C in summer. The mean temperature was 18.3 ± 2.9°C, with the lowest temperature (10.9°C) in July and the highest temperature (23.7°C) in December (Figure 2c). In addition to seasonal variations, stream temperature showed strong synoptic variability with rapid temperature changes of up to 5°C at time scales of 5 to 7 days. Water temperature changed mostly synchronously with air temperature and short wave radiation and discharge peaks were often accompanied by rapid drops in water temperature (Figure 2).

Simulated water temperature for the present state of shading was in very good agreement with the measurements, with a RMSE of 0.58°C and a mean absolute error of 0.47°C. Linear regression of measured versus simulated water temperatures resulted in a slope of 1.0, an intercept of −0.27°C and a R^2 of 0.98, indicating that the simulation was unbiased. Moreover, also the temporal dynamics of Passaúna river water temperatures was well reproduced by the model considering the present state of shading (Figure 2c).

The scenario with full shading ($f_{shade} = 0.85$ for all river reaches) resulted in a moderate reduction of the river water temperature at the reservoir inflow in comparison to the present state (Figures 2 and 3). The simulated temperature differences ranged between −0.1°C and − 2.0°C with an average of −0.8°C. Owing to the already relatively high degree of shading for the present state ($f_{shade} = 0.55$ through 0.85), maximum shading only showed moderate effects on river water temperature at the reservoir inflow.

The absence of shading ($f_{shade} = 0$ for all river reaches) resulted in significantly higher inflow temperature (Figures 2 and 3). Compared to the present state of shading, the increase of daily mean inflow temperature varied between +0.1 and +4.7°C with an average of +2.2°C. This increase is slightly non-linear with higher values in summer, when water temperature was high (Figure 3). This non-linearity is due to the higher contribution of shortwave radiation to the overall energy balance during summer. The largest differences occurred in December 2018, when high shortwave radiation and low flow situations coincided (Figure 2). The difference in water temperature for the two contrasting scenarios without shading and with full shading ranged between +0.3 and +6.7°C with an average difference of +3.0°C (Figure 2c).

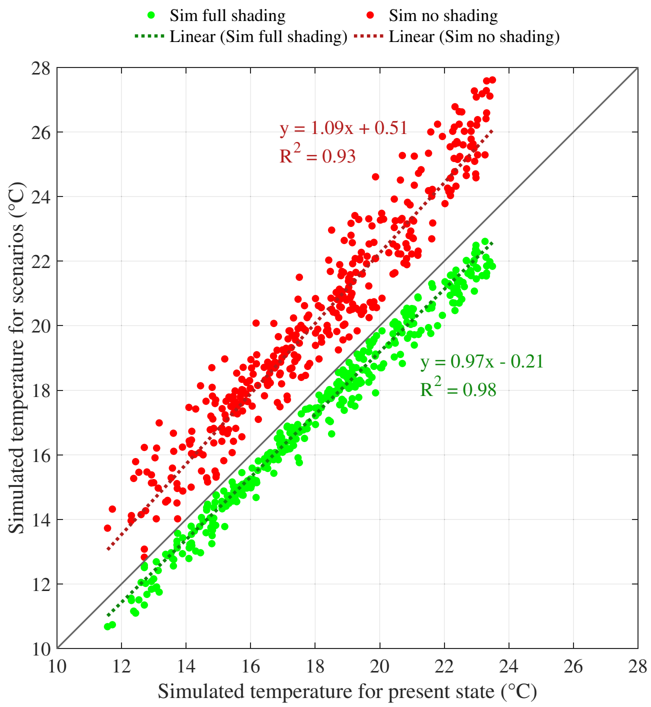

FIGURE 3 Comparison of daily mean stream water temperature at Minidot simulated for the present state of shading with scenarios of full shading (green symbols) and no shading (red symbols) in the upstream stream network. Dotted lines show linear regressions for the two scenarios in the respective color. Regression equations and coefficient of determination (R^2) are provided as text labels. The solid grey line shows a 1:1 relationship [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Reservoir temperature stratification

Water temperature in the reservoir was 21.6 ± 3.5°C at the water surface, and 19.1 ± 2.0°C at the bottom. With persistent temperature differences between the surface and the bottom (1.4 to 7.2°C), the reservoir was stably stratified until the middle of April and from September 2018 (Figure 4). During the stratified period, water surface temperature showed synoptic variability, but with smaller amplitude than stream temperature (Figure 4). The vertical temperature stratification was rather continuous and did not show well-defined layers of epilimnion, metalimnion and hypolimnion. Below an upper mixed layer of seasonally varying depth, temperature decreased with increasing depth at a nearly constant rate. Bottom water temperature showed little variations and increased nearly linearly over time throughout the stratified period. The stable stratification broke down in April, followed by a period of intermittent mixing and stratification between May and August. The seasonal mixing dynamics of the reservoir can therefore be classified as discontinuous warm polymictic (Lewis Jr, 1983).

3.4 | Reservoir inflow regime

Based on observed daily-mean values of inflow and reservoir water temperature, underflow was the dominant inflow regime of the river in the reservoir, with a relative frequency of occurrence of 63% throughout the monitored period. Interflows were present for the remaining time (37%) and overflows were not existent. Interflows were predominant in spring and summer (Figure 5a), and for the rest of the year underflows were prevalent. The presence of underflows promoted the frequent development of weak stratification also during the mixed period between April and August by transporting cooler river water to the bottom of the reservoir.

In good agreement with the analysis based on measured water temperature, simulated inflow temperature for the present state of shading resulted in a dominance of underflows (67%), whereas overflows were not observed. Also, the seasonal and short-term variability of inflow regimes was well reproduced in the simulations (Figure 5b).

In the simulation for full shading of the stream network, the general distribution of inflow regimes did not change much in comparison to the present state. The relative frequency of occurrence of underflows increased to 81% (Figure 5c), due to the decrease of inflow temperatures (Figure 4).

For the simulated scenario with no shading of the streams, however, inflow regimes changed considerably (Figure 5d). Interflows became the predominant (51%) flow path, and the occurrence of underflows was reduced to 34%. Overflows occurred during 15% of the time. Overflows only occurred during the winter and spring seasons, when the temperature in the Passaúna River exceeded the surface temperatures of the reservoir. During summer, when the temperature was highest, the river temperature was often close to the reservoir surface temperature (Figure 4), but overflows did not occur.

4 | DISCUSSION

4.1 | Effect of riparian shading on stream water temperature

The results presented in this study are based on simulated daily mean water temperature for a relatively well shaded river system at a latitude of $-25°30'$. According to our results, changing the present state of riparian vegetation to no shading would increase stream water temperature near the reservoir inflow by $+2.2°C$ on average, with a maximum increase of daily mean temperature of $+4.7°C$. The difference between the no shading scenario and the full shading scenario was $+3.1°C$ on average, with a maximum of $+6.7°C$.

A quantitative comparison of the observed effect of shading on stream temperature with other investigations is difficult, mainly because of differences in meteorological conditions, in residence times of the water and in methodological approaches. In particular, most other studies were conducted in North America or Europe at higher latitudes with different meteorological conditions. Moreover, results are normally reported for summer conditions and maximum differences only, and not for a yearly average. Nonetheless, our findings may be compared with other results in the literature, qualitatively. For example, several empirical studies, mainly from the Pacific Northwest region in North America (latitude $\sim+45°$ to $+55°$), showed that forest clear-cutting leads to an increase of maximum summer water temperatures of headwater streams commonly in the range of $+4°C$ to $+9°C$ (see reviews in Beschta et al., 1987; D. R. Moore et al., 2005). Empirical studies in the United Kingdom showed that the effect of forest cover as compared to open land on water temperature may vary considerably. Looking at the yearly average, effective shading by forest vegetation in most cases led to moderate

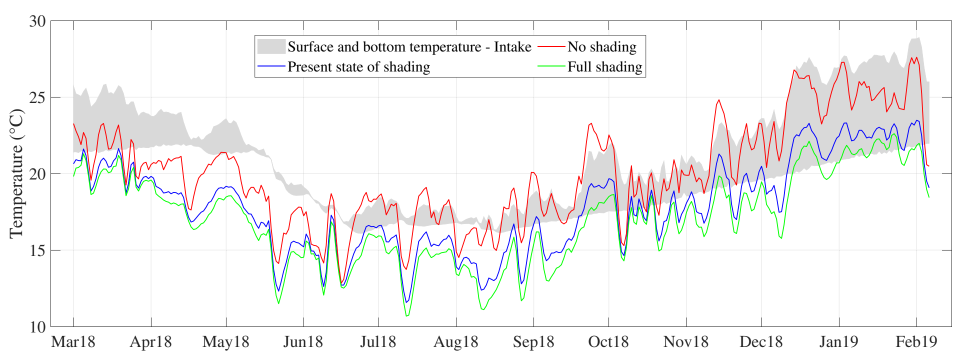

FIGURE 4 Time series of daily-mean water temperature in Passaúna reservoir and its main inflow: The filled gray area marks the range of temperature measured at the surface and the bottom of the reservoir. Colored lines show simulated temperature of the Passaúna River at the reservoir inflow, blue represents the present state of shading, green represents the full shading scenario and red the no-shading scenario of the river network upstream of the reservoir [Color figure can be viewed at wileyonlinelibrary.com]

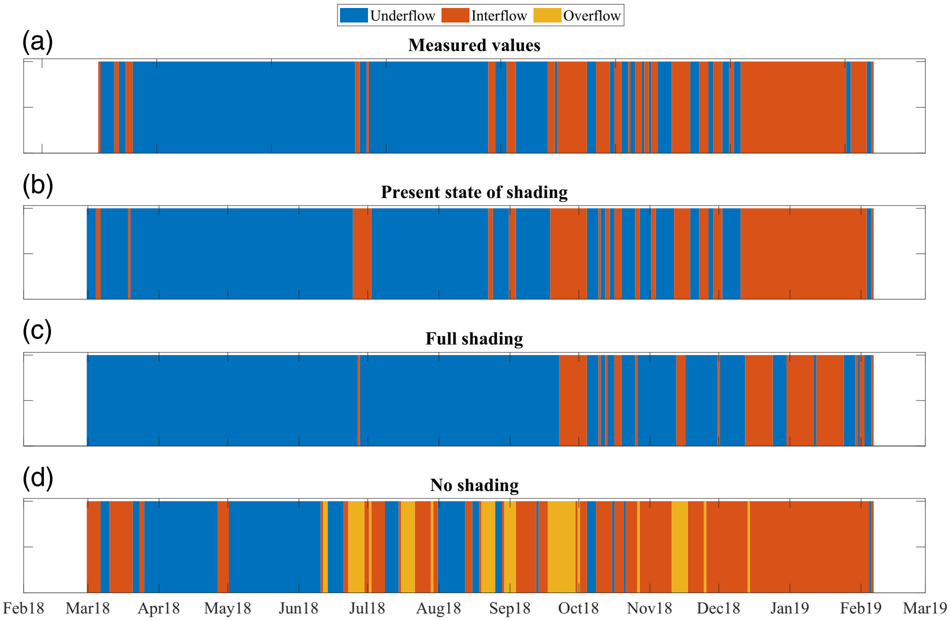

FIGURE 5 Time series of inflow regimes of the Passaúna River into the reservoir. Different flow paths are presented as vertical bars with color denoting underflow (blue), interflow (orange) and overflow (yellow) situations with a temporal resolution of one day. (a) Results based on measured inflow temperature. (b) Result based on simulated river temperatures for the present state of shading of the upstream stream network. (c) Result based on simulated river temperatures for the full shading scenario. (d) Result based on simulated river temperatures for the no shading scenario [Color figure can be viewed at wileyonlinelibrary.com]

temperature reductions of less than 1°C (e.g., Broadmeadow, Jones, Langford, Shaw, & Nisbet, 2011; Brown, Cooper, Holden, & Ramchunder, 2010; Crisp, 1997; Dugdale et al., 2018; Stott & Marks, 2000; B. Webb & Crisp, 2006). However, mean summer temperatures may be reduced more effectively by approximately 1–3°C, and maximum reduction of water temperature may be as high as 5°C (Broadmeadow et al., 2011; Brown et al., 2010; Dugdale et al., 2018; B. Webb & Crisp, 2006).

Recently Garner et al. (2017) investigated the effects of riparian vegetation density, stream orientation and flow velocity in a 1,050 m long reach of the Girnock Burn in Scotland (latitude: +57°) with a sophisticated modeling approach by applying the meteorological conditions of a single summer day with almost clear sky and high rates of solar radiation. For high flow conditions with short residence times of approximately 1.75 hr, stream shading showed a moderate effect on mean daily water temperature in the range of 1.5°C. However, for low flow conditions with a sufficiently long residence time of 12.5 hr, daily mean water temperature for little shading (10–20% canopy density) was about 4.5°C higher than for simulations with a high rate of shading (70–90% canopy density). Similarly, simulation results of Trimmel et al. (2018) for a 50 km reach of the 4–10 m wide river Pinka in Austria (latitude: +47°) demonstrated the potential difference between a no vegetation and a maximum vegetation scenario. According to their results mean water temperatures during the heat wave of August 4 through August 8, 2013 were approximately 4°C lower for the maximum vegetation scenario than for the no vegetation scenario.

The maximum difference between the no shading and the full shading scenario of +6.7°C for Passaúna River is well in the range of the empirical studies for the Pacific North West (D. R. Moore et al., 2005). Also, the difference between the yearly average and the maximum effect in summer is in good accordance with the findings from the United Kingdom (Brown et al., 2010; Dugdale et al., 2018; B. W. Webb et al., 2008). However, our simulated effect of riparian shading on stream water temperature of Passaúna is somewhat higher than the empirical and modeling results from Europe and North America. This may partly be due to differences in residence time. We considered the effect of shading of the complete river network of a relatively large catchment, whereas the other studies mainly looked at small headwater streams with shorter residence times. In the case of river Pinka in Austria only the main river was assumed to be shaded, whereas inflowing tributaries were assumed to have the same temperature in all scenarios. Thus, shorter residence times in other studies may have contributed to the less pronounced effects of shading. Moreover, we neglected the effect of riparian vegetation on longwave radiation in our study, which increases the energy input at the water surface slightly. This might lead to a small systematic overestimation of the effect of stream shading on water temperatures in our study. Finally, and probably most importantly, the effect of riparian shading via blocking of incoming shortwave radiation is likely to be considerably higher at a low latitude of −25° (Passaúna) than at the much higher latitudes of the other study sites (~45° to 57°).

Therefore, in summary, our scenario results for the effect of shading on river water temperature are broadly in line with the literature and can be considered as realistic, even though we could not compare them to other findings from the tropics. Considering the fact that the focus of the present study is not on precise predictions, but results are rather used to demonstrate the potential impact of stream shading in a catchment on a downstream reservoir, the accuracy of our shading scenarios appears to be sufficient.

4.2 | Stream shading in the catchment affects reservoir mixing and stratification

Vertical mixing in reservoirs can be strongly suppressed by temperature stratification, which develops as a consequence of enhanced water depth and reduced flow velocity in comparison to free-flowing rivers. Vertical temperature gradients develop in response to solar heating of the surface layer, or by lateral density currents formed by inflowing rivers. The latter mechanism depends on stream temperature of the inflow and has been well documented in many reservoirs and studied in laboratory experiments (Alavian, Jirka, Denton, Johnson, & Stefan, 1992; Imberger & Hamblin, 1982; Wells & Nadarajah, 2009). However, the effect of catchment properties on the flow paths of inflowing water has not explicitly been studied. Here, we analyzed the potential effect of riparian stream shading in the catchment on density currents in the reservoir by combining catchment-scale hydrological modeling with temperature observations in a tropical drinking water reservoir. We found that the difference of inflow temperature resulting from the presence and absence of stream shading in the catchment significantly changed the inflow regime, which can affect vertical stratification and mixing in the reservoir. For a high degree of shading, as for the present state of the Passaúna catchment, the stream entered the reservoir predominantly as underflows, along the bottom of the reservoir. In the absence of shading, the higher inflow temperature led to a reduction of the occurrence of underflows and promoted overflow situations. Both types of density currents contribute to vertical temperature stratification in the reservoir. The predicted inflow of warmer water to the reservoir in the absence of shading occurred mainly during winter and spring and can result in increasing the frequency and duration of stratified periods during the mixed season. During the stratified season (summer and autumn), the predicted reduction of underflow situations can be expected to reduce the stability of vertical temperature stratification. Interflows were the most frequent inflow regime in the no-shading scenario and the intrusion depth was shallower compared to the present state. Tracer studies on a plunging river in a Mediterranean reservoir revealed that a fraction (and possibly all) of river inflow entrains into the surface mixed layer, when the density current forms intrusions at the top of the stratified part of the water column (Cortés, Fleenor, Wells, de Vicente, & Rueda, 2014).

4.3 | Implications for reservoir water quality

The observed change in inflow regime for the no shading scenario potentially affects water quality in the reservoir. The occurrence of overflows, which are not present for the present state of shading, facilitates nutrient transport to the photic zone and therewith promotes algae growth (Ayala et al., 2014; Rueda et al., 2007). The combination of excessive nutrient supply at the water surface and reduced vertical mixing during these conditions provide ideal conditions for harmful cyanobacterial blooms (Paerl & Otten, 2013), which are currently not present in Passaúna reservoir. In consequence of the reduced underflows, the transport of oxygen with the inflowing water to greater depths would be reduced, leading to a prolongation of periods of anoxia. Anoxic bottom water further increases internal loading with nutrients from the sediments (Søndergaard, Jensen, & Jeppesen, 2003), as well as the release of anoxic products such as methane, hydrogen sulfide and metals (Beutel & Horne, 1999). In consequence, the water quality in the reservoir can be expected to deteriorate for the scenario without stream shading in the catchment in comparison to the present and full shading conditions.

Given the high degree of forested area in the catchment of Passaúna reservoir (44%), no shading may represent a scenario of extreme land use change at first glance. However, increasing urbanization and agricultural land use in the growing metropolitan area of Curitiba exert a strong anthropogenic pressure on the Passaúna catchment, which may lead to significant deforestation. Furthermore, stream shading does not have an instantaneous effect on water temperature, but rather needs some residence time (i.e., flow distance) to exert its effect (Bartholow, 2000; Kalny et al., 2017; Regenauer et al., 2019). Thus, even if deforestation is restricted to the upstream part of the catchment, it may still lead to increased water temperatures at the downstream inflow of the reservoir.

The strong control of catchment properties on reservoir water quality has been extensively studied in terms of hydrological characteristics and in respect to the input of suspended and dissolved substances, including nutrients and pollutants (Beaver et al., 2014; Jones, Knowlton, & Obrecht, 2008; Knoll et al., 2015). The effect of riparian shading, which is closely linked to land use in the catchment, has not been considered. Our results demonstrate, that changes in stream shading should be included in management scenarios of the catchment area which aim at safeguarding reservoir water quality.

4.4 | Limitations of the present study

The good agreement between stream temperature simulations for the present state of shading with observations suggests that the applied integrated water balance and stream water temperature model LARSIM-WT is a robust tool for estimating the effect of shading on stream water temperature. However, by only considering the temperature difference between the inflowing water and reservoir stratification, we applied a rather crude approach for characterizing the inflow conditions. The plunging depth of density currents in reservoirs is known to depend on geometry of the inflow region and volumetric discharge, wind mixing and many other factors, while the plume formed by the density current is subject to dispersion (Cortés et al., 2014; Imberger & Hamblin, 1982). Moreover, the changing inflow will further change reservoir stratification, which was neglected in this study where we used observed reservoir temperature in all scenarios. In contrast, the most relevant change was the increase of overflows, where the inflowing water stays in the upper mixed layer. Because surface water temperature is mainly driven by air temperature, only minor changes of reservoir stratification are expected in this case. More realistic descriptions of density currents and projected changes in water quality in response to changing inflow temperature requires more detailed hydrodynamic modeling (e.g., Long, Ji, Liu, Yang, & Lorke, 2019; Rueda et al., 2007) and further assumptions on boundary conditions, which would make the results more accurate, but also more case specific.

Our results were obtained for a small reservoir in the tropics, which was chosen for reasons of data and model availability. Although Passaúna reservoir can be considered as being representative for a large number of impoundments in terms of reservoir size, both the effect of riparian shading on stream temperature and the inflow dynamics are affected by many factors, including catchment and reservoir size, water depth and geographic location. For example, in larger rivers (more than approximately 15–30 m wide), shading certainly has limited effect on water temperature, as only a fraction of the water surface is subject to shading by riparian vegetation (e.g., DeWalle, 2008; R. Moore et al., 2014; Regenauer et al., 2019). Given the complex and site-specific conditions of the underlying processes, a more detailed assessment of the relevance of stream shading in the catchment on the inflow regime in reservoirs requires further analysis for a broader range of reservoirs and catchments in future studies.

5 | CONCLUSIONS

Stream shading is a relevant factor for river temperature, and its alteration can significantly affect reservoirs hydrodynamics and potentially water quality. Deforestation in the catchment and the removal of tall vegetation along riparian zones of streams may lead to increased river water temperatures, as can be predicted robustly by a combined water balance and water temperature model, such as LARSIM-WT. These changes of the water temperature of inflowing rivers can be expected to lead to a degradation of water quality in the downstream reservoir due to changes in reservoir hydrodynamics. Despite rather crude assumptions with respect to the hydrodynamics at the reservoir inflow and site-specific simulations, our findings revealed a so-far overlooked mechanism by which reservoir water quality can be affected and potentially also manipulated by catchment properties and land use management. Given the potential relevance of this process for reservoir water quality, the site-specific effects of riparian shading in the catchment should be considered with more realistic approaches to the hydrodynamics at the inflow and for a broader range of reservoirs.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.4746288.

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