

Article

# Groundwater Recharge Potential for Sustainable Water Use in Urban Areas of the Jequitiba River Basin, Brazil

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**Abstract:** The zoning of groundwater recharge potential would be attractive for water managers, but is lacking in many regions around the planet, including in the Jequitiba River basin, Minas Gerais, Brazil. In this study, a physically based spatially distributed method to evaluate groundwater recharge potential at catchment scale was developed and tested in the aforementioned Jequitiba River basin. The data for the test was compiled from institutional sources and implemented in a Geographic Information System. It comprised meteorological, hydrometric, relief, land use, and soil data. The average results resembled the annual recharge calculated by a hydrograph method, which worked as validation method. The spatial variation of recharge highlighted the predominant contribution of flat areas, porous aquifers, and forested regions to groundwater recharge. They also exposed the negative effect of urbanization. In combination, these factors elected the following sectors of the Jequitiba River basin as regions of high recharge potential: the south-southeast part of the headwaters in Prudente de Moraes; Sete Lagoas towards the central part of the basin; and the region between Funilândia and Jequitiba, near the Jequitiba river mouth. Some management practices were suggested to improve groundwater recharge. The map of groundwater recharge potential produced in this study is valuable and is therefore proposed as tool for planners in the sustainable use of groundwater and protection of recharge areas.

**Keywords:** groundwater recharge; recharge zones; river basin; spatialization; relief; geology; forest; urbanization; water resource management; land use policy

## 1. Introduction

Water is a naturally circulating resource that is constantly recharged [1]. However, by 2025 it is estimated that around 5 billion people, out of a total population of around 8 billion, will be living in countries experiencing water stress [2]. Climate change has the potential to impose additional pressures in some regions. It is therefore urgent to chart our water future [3]. A river basin is the natural boundary where the relief directs the water to a common point known as river mouth. Incorrect management of river basins can seriously affect water availability, damaging both surface water and groundwater. One can refer, for example, the negative effect of pavement or other civil constructions

on water infiltration in the soil [4,5]. In addition, other problems, such as intensification of erosive processes, can occur depending on the intensity level of soil waterproofing and compaction [6–10].

The percolation of water through the porous spaces of the soil and rocks is an important process to groundwater recharge, directly affecting the maintenance of various human activities, such as the water supply to urban centers, industrial parks, and agricultural activities [11–16]. The water stock in underground systems is connected to surface soil use conditions. Significant changes in the landscape can alter water regimes and groundwater quality [17]. Information on the relationships between surface water and groundwater allows a better water use through data that assists on the sustainable management of water resources [18–22]. Groundwater recharge zones are places where the ground surface allows water infiltration and percolation through the soil [23–27]. Water can be retained in the soil, reach the vadose zone or arrive at a geological system that can store and distribute it [15,28–31]. Recharge can be favored through storage in small dams or rainwater harvesting systems [32–37], which also aid the prevention of floods [38].

Despite the importance of recharge zones, no public policies are in force in Minas Gerais State (Brazil) to promote their sustainable use. The starting step comprises the identification and mapping of recharge areas, but this phase has not commenced. It is worth reinforcing that the inadequate use of recharge zones can reduce water infiltration in the soil through waterproofing and compaction; and low infiltration rates can concentrate and increase surface runoff, generating problems in urban centers such as flooding [39–43]. In addition, the intense exploitation of water resources in urban areas can generate water scarcity and even depletion [44–46]. At catchment scale, the inadequate managing of water sources and recharge areas can reduce water availability and increase the vulnerability of surface and groundwater to contamination [46–57]. It is therefore time for policy makers and water planners to start a robust assessment of groundwater recharge potential. Robustness relies on a thorough collection of information on physical-environmental factors, such as soil characteristics, geology, vegetation cover, and relief. Information on these issues allows the use of water volumes according to the natural capacity of the system [16].

Direct and indirect methods can be used to assess groundwater characteristics including recharge. Direct methods comprise geological and geophysical explorations, gravimetric and magnetic methods, and drilling tests. Indirect methods include hydrological modeling [58–66] using geographic information systems (GIS) combined with fieldwork, geochemical tracers [67–69], survey of specialized literature for standard values [15,16,70,71], among others. The choice for a method (direct or indirect) should consider the precision level needed, the project execution, and the resources available. Therefore, appropriate specific methodological approaches should be applied to each local condition that the river basin encompasses.

Significant amounts of groundwater are withdrawn from the Jequitiba river basin, because this catchment is located in a populous region of Minas Gerais State, which hosts a large population and several industries from different segments [72]. According to Pessoa [73], in 1993, the water for domestic use in the largest town in the basin (Sete Lagoas, representing 94.3% of the entire population) was supplied by groundwater resources, namely 65 drilled wells with an average yield of  $8.0 \text{ L s}^{-1}$  ( $520 \text{ L s}^{-1}$  of total yield). In those days, the population of Sete Lagoas was nearly 150,000 and consumed approximately  $200 \text{ L habitant}^{-1} \text{ day}^{-1}$ . Thus, the pressure over the drilled wells was evaluated in 16 h of pumping every day and considered preoccupying. Moreover, the quality of these resources was threatened because the domestic sewage system was lacking. The situation of Sete Lagoas was re-evaluated in 2008 by Botelho [74], with similar conclusions. 25 years after the evaluation of Pessoa, the number of drilled wells raised from 65 to 94 (44% increase), keeping a similar average yield ( $7.8 \text{ L s}^{-1}$ ), while the population of Sete Lagoas raised from 150,000 to 220,000 (47% increase). The sewage system was still lacking or incomplete. In 2014, Galvão et al. [75] evaluated the effects of pumping in the geometry of hydraulic heads within the area of Sete Lagoas where the number of drilled wells and pumping rates are larger. A hydraulically depressed area was delineated around the older wells (1942) where depths to the water have ranged from 14 m post drilling to 62 m in 2012

(48 m drawdown in 70 years). According to age versus drawdown data available in the study of Galvão, it is possible to estimate an average of  $0.9 \text{ m year}^{-1}$  of drawdown within the depressed area, caused by excessive pumping. The study of Galvão also suggested the link of this hydraulic head depression to the development of suffosional sinkholes. Moreover, the results of Botelho's interviews to SAAE (Autonomous Service of Water and Sewage) employees refer that "... as the urban space expands, the municipal authorities do not improve the supply and distribution systems, and do not prioritize studies and planning for the occupation of space ...". It is therefore urgent to help the municipality accomplishing the task, through provision of relevant information and data for planning such as the spatial distribution of groundwater recharge potential.

The general goal of this study was to estimate groundwater recharge potential within the Jequitiba River basin, to identify and delineate preferential areas for restoration, recovery, and protection. To accomplish this purpose, the following specific objectives had to be accomplished: (a) develop a physically based spatially distributed model to estimate groundwater recharge potential at catchment scale; (b) compile a diversified set of geospatial information, including meteorological, hydrometric, geologic, relief, land use, and soil data; (c) run the model using the compiled data and produce the final groundwater recharge potential map; (d) validate the model through calculation of groundwater recharge using an independent approach based on independent data, namely stream flow recession analysis.

## 2. Materials and Methods

### 2.1. Study Area

The Jequitiba River basin (JRB) crosses the municipalities of Sete Lagoas, Prudente de Morais, Funilândia, Jequitiba, and Capim Branco, in the state of Minas Gerais (MG), Brazil, and covers approximately 57,148 hectares (Figure 1a). The JRB is managed by the Water Resources Planning and Management Unit (UPGRH) Rio das Velhas (SF5). The main highways that cross the JRB are the BR040, MG024, and MG238. According to the 2014 Water Resources Plan for the Rio das Velhas River Basin, the Jequitiba River Strategic Territory Unit has a population of approximately 145,729 inhabitants, mostly concentrated in urban areas since 97.6% of them live in urban areas and 2.4% in rural areas. The largest municipality in the basin is Sete Lagoas, which accounts for 94.3% of the total population.

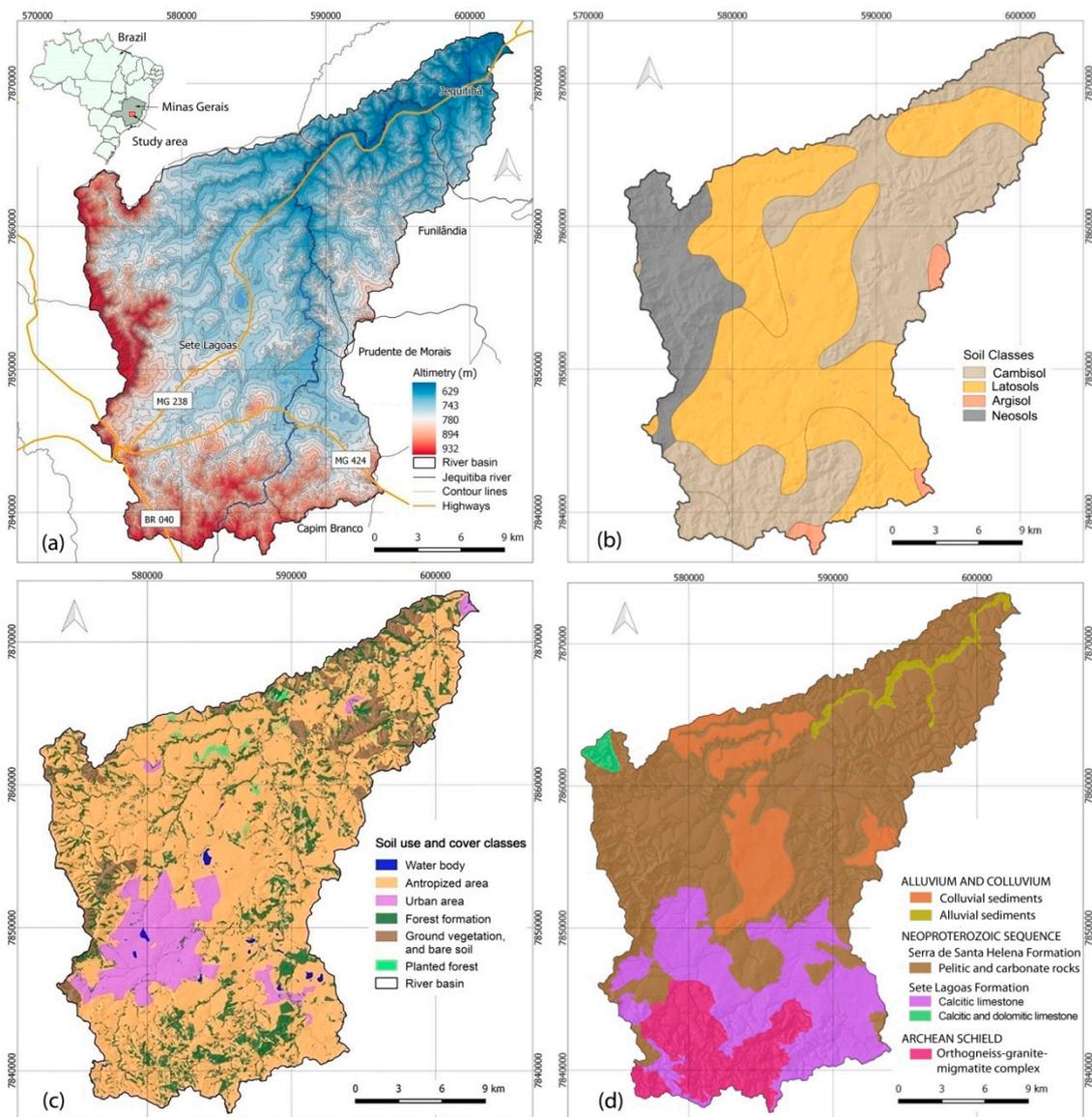
The climate, according to Köppen's classification, is the subtropical (Cwa), characterized by dry winter and hot summer. The rainfall regime of the area in 2000 to 2016 presented monthly precipitation of 3 mm to 319 mm, with a rainy season from October to March, and a dry season from April to September. The mean annual rainfall in the same period was 1291.2 mm, while the mean temperatures varied from  $18^\circ\text{C}$  in July and  $24^\circ\text{C}$  in January–February, with a mean value of  $21.8^\circ\text{C}$ .

The soil classes found in the JRB (Figure 1b), according to the Brazilian Soil Classification System, are Latossolos (49.6%), Cambissolos (36.7%), Argissolos (1.3%), and Neossolos (12.2%) [76].

Considering the land use and cover map developed by the reference [77], almost 39,000 ha (68%) of the JRB is used for anthropogenic activities, comprising livestock pasturing or agriculture, which are distributed throughout the drainage basin domain (Figure 1c). Forest is the second most frequent class of land use in the JRB, with 15.8% of the area, followed by the urban area class, with 9.3% of the JRB area.

The geology is characterized by a stratigraphic sequence comprising an Archean crystalline basement made of orthogneisses, granites and migmatites, overlaid by Neoproterozoic carbonate rocks of Bambuí Group, namely calcite and dolomite limestones from Sete Lagoas Formation and pelitic rocks with interlayered carbonates from the Serra de Santa Helena Formation. Along the main water courses, the Neoproterozoic sequences are overlaid by terrigenous rocks composed of alluvium and colluvium sediments [78]. The spatial distribution of outcrops is illustrated in Figure 1d, indicating a predominance of pelitic rocks (57.6%), followed by limestones (20%), Archean basement (10%), colluvium (10%), and alluvium (8%) [79]. When the geologic map is compared with the soil map, a

spatial association between lithotypes and soil types becomes apparent: the cambisols developed from the Archean rocks as well as from pelitic rocks cropping out in the catchment lowlands; the neosols developed from pelitic rocks cropping out in the catchment highlands; the latosols developed from limestones and terrigenous rocks.



**Figure 1.** (a) Location of study area: Jequitiba River basin, Minas Gerais, Brazil; (b) soil map of Jequitiba River basin. (c) Land use and cover map of Jequitiba River basin; (d) lithologic map of Jequitiba River basin. The geographic reference for the maps is the Universal Transverse Mercator (UTM) projection system, Geocentric Reference System for America (SIRGAS) 2000 datum, 23 south time zone.

The hydrogeology is characterized by fractured aquifers composed of Archean rocks, fractured-karst aquifers composed of Serra de Santa Helena pelitic rocks interlayered with carbonates, karst aquifers composed of Sete Lagoas limestones, and porous aquifers composed of terrigenous rocks and the soil layer that can be thick [80]. Specific flows are very low in the fractured aquifers (average:  $0.52 \text{ m}^3 \text{ ha}^{-1} \text{ m}^{-1}$ ), low in the fracture-karst aquifers (average:  $20.84 \text{ m}^3 \text{ ha}^{-1} \text{ m}^{-1}$ ), and high in the karst aquifers (can reach  $264 \text{ m}^3 \text{ ha}^{-1} \text{ m}^{-1}$ ) (<http://www.cprm.gov.br>). Given the thickness of soil and saprolite layers in large portions of the basin, aquifer recharge is largely conditioned by infiltration and storage in the soil. Latosols favor infiltration because soil particles in this soil type are mostly arranged

as micro aggregates with high hydraulic conductivity. In the cambisols, water does not infiltrate easily, because soil particles are sometimes cemented or compacted and disposed in laminar layers [80].

## 2.2. Materials and Software

The materials used in this study are indicated in Table 1 and comprised: (a) a Digital Elevation Model (DEM) ALOS PALSAR with a spatial resolution of 12.5 meters [81]; (b) a land use and cover map at scale 1:25,000 [77]; (c) the soil map of Minas Gerais state at scale of 1:650,000 and corresponding data on total porosity and hydraulic conductivity [76]; (d) precipitation and real evapotranspiration data from weather stations in the municipalities of Belo Horizonte (BH), Sete Lagoas (SL), Conceição do Mato Dentro (CMD), and Florestal (FLT) [82]; (e) hydrometric data of station 41410000, in the mouth of Jequitiba River [83]; (f) the geological map of Minas Gerais state at scale 1:1,000,000 [79]; (g) data from the Rural Environmental Registry (CAR) of the municipalities in the JRB [84]; (h) Population data relative to the studied area [72]; (i) Quantum Geographic Information System (QGIS) program, version 2.18.4 [85].

**Table 1.** Materials (spatial data, climatic records, additional information), uses in the recharge potential evaluation model, and URLs of websites used for downloading the data.

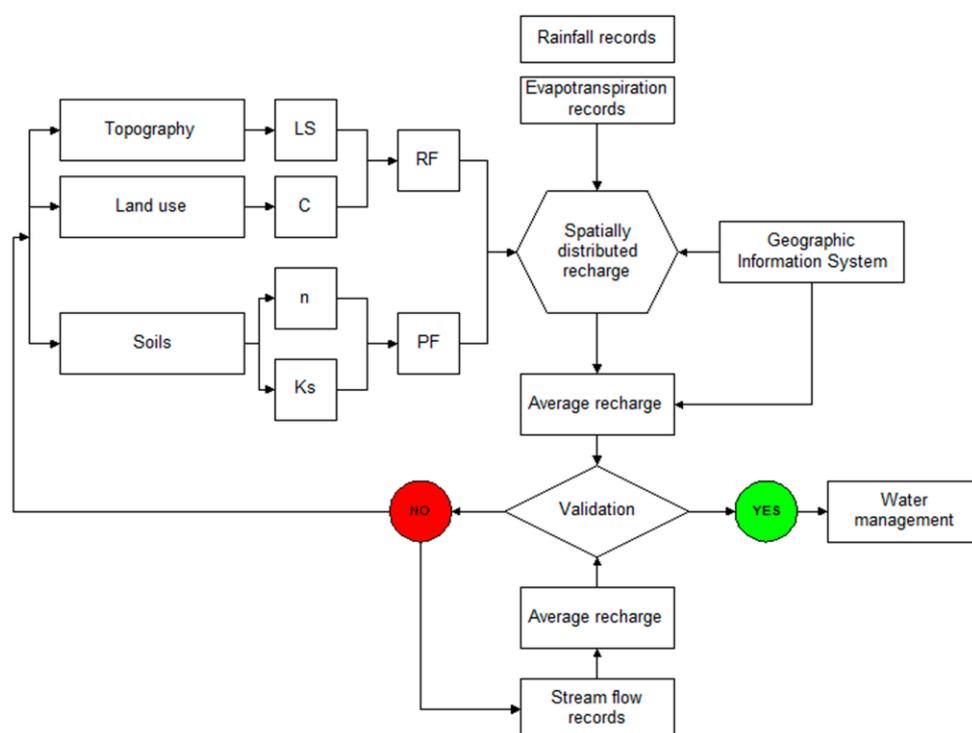
Data Type	Use in the Recharge Evaluation Model	URL of Website
Digital elevation model	Calculation of slope length and steepness factor (Equation (1))	<a href="https://www.asf.alaska.edu">https://www.asf.alaska.edu</a>
Land use and cover map	Calculation of runoff parameter (Equation (1))	<a href="http://geo.fbds.org.br">http://geo.fbds.org.br</a>
Soil map and associated porosity and hydraulic conductivity data	Calculation of percolation factor (Equation (2))	<a href="http://www.dps.ufv.br">http://www.dps.ufv.br</a>
Rainfall and evapotranspiration data	Calculation of recharge potential (Equation (3))	<a href="http://www.inmet.gov.br">http://www.inmet.gov.br</a>
Stream flow data	Validation of recharge potential using an independent method (recession analysis)	<a href="http://www.snirh.gov.br/hidroweb">http://www.snirh.gov.br/hidroweb</a>
Geologic map	Information for discussion	<a href="http://www.portaldageologia.com.br">www.portaldageologia.com.br</a>
Administrative data	Additional information	<a href="http://www.car.gov.br">http://www.car.gov.br</a>
Population data	Additional information	<a href="http://www.sidra.ibge.gov.br">http://www.sidra.ibge.gov.br</a>

## 2.3. Methods

The method proposed in this study to evaluate groundwater recharge is spatially distributed and based on water balance. The general workflow is illustrated in Figure 2 and was developed in five main stages: (i) acquisition of topographic, land use and soil maps as well as compilation of climatic records (precipitation and real evapotranspiration); (ii) calculation of the surface runoff factor (RF), based on evaluation of hillside lengths and slopes (LS factor) as well as on runoff coefficients (C); (iii) calculation of water percolation factor (PF), based on soil characteristics (total porosity— $n$ ; hydraulic conductivity— $K_s$ ); (iv) calculation of groundwater recharge in each point of a catchment and an average value for the entire catchment, using a geographic information system; (v) validation of results, through comparison of previously calculated average recharge with a counter value estimated by an independent method (e.g., the hydrograph recession method based on stream flow analysis). The five stages are described in detail in the following paragraphs.

In the first stage, the annual averages for precipitation and real evapotranspiration in the hydrological stations of municipalities near the study area (SL, BH, CMD, and FLT) were estimated using data from 2000 to 2018. Longer time series would be more adequate for recharge estimation in a

changing climate, but they were not available. The information was interpolated by calculating the inverse distance weighting (IDW) raised to the power of two. This interpolator was used because it reduces the influence of the values recorded in the farthest stations from the JRB, with higher weights for the values of the nearest stations [86]. Subsequently, the data was spatialized and cut to the limits of the study area.



**Figure 2.** Workflow for the estimation of groundwater recharge potential.

In the second stage, the land use and cover map and topographic information derived from the digital elevation model (slope length and steepness factor, LS-factor) were used to calculate a surface runoff factor, based on the method proposed by Böhner and Selige [87]. The surface runoff factor was calculated according to Equation (1):

$$RF = 1 - (C + LS_{Fuzzy}) \quad (1)$$

where  $RF$  is the surface runoff factor (dimensionless),  $C$  is the coefficient of surface runoff (dimensionless; adopted values in Table 2), and  $LS_{Fuzzy}$  is the slope length and steepness factor estimated using the method of Desmet and Govers [88]. The  $LS_{Fuzzy}$  parameter was subsequently adjusted to a range of 0 to 1 by a fuzzy logic algorithm; the closer to 1, the steeper the slope is in the landscape.

**Table 2.** Coefficient of surface runoff adopted for each soil use and cover class in the Jequitiba River basin, Minas Gerais (MG), Brazil (Adapted from [89]).

Soil Use and Cover Classes	C
Anthropized area	0.5
Urban area	0.85
Forest formation	0.1
Planted forest	0.13
Ground vegetation, and bare soil	0.6

In the third stage, the soil map and information on soil total porosity ( $n$ ) and hydraulic conductivity ( $K_s$ ) were used to calculate a percolation factor ( $PF$ ) for each soil class in the tested basin. The values of  $K_s$  and  $n$  were mostly compiled from field studies published by Pedron [90,91]. The values used in the modeling are depicted in Table 3. The percolation factor was evaluated through Equation (2):

$$PF = n \times K_{s_{Fuzzy}} \quad (2)$$

where  $PF$  is the water percolation factor (dimensionless), and  $K_{s_{Fuzzy}}$  (dimensionless) is the soil hydraulic conductivity adjusted to a range of 0 to 1 through fuzzy logic; the closer to 1, the greater the soil hydraulic conductivity in the specific class.

**Table 3.** Total porosity and hydraulic conductivity values adopted for each soil type in the Jequitiba River basin, MG, Brazil (main source: field studies of Pedron [90,91]).

Soil Type	$K_s$ (mm/h)	Total Porosity
Cambisol	16	0.53
Latosol	52	0.69
Argisol	19	0.44
Neosol	32	0.43

In the fourth stage, values were calculated for the groundwater recharge potential in each point of the studied catchment, using Equation (3):

$$RPot = [(P - ETr) \times RF \times PF] \times 10 \quad (3)$$

where  $RPot$  is the groundwater recharge potential ( $m^3 \text{ ha}^{-1} \text{ year}^{-1}$ ),  $P$  is the annual average precipitation ( $mm \text{ year}^{-1}$ ),  $ETr$  is the average real evapotranspiration ( $mm \text{ year}^{-1}$ ),  $RF$  is the runoff factor; and  $PF$  is the percolation factor.

The results were validated in the fifth stage, by comparing the total recharge volume of the basin with the total estimated recharge volume by the recession curve analysis method, using the Jequitiba River hydrograph. Data from 2010 to 2012 was used because it was the most recent period in which water flow records had the greatest continuity in the historical series without failures or missing data. These data were used to calculate the Maillet equation (Equation (4)) [65,92]:

$$Q_t = Q_0 e^{-\alpha t} \quad (4)$$

wherein  $Q_t$  is flow at time  $t$  ( $m^3 \text{ s}^{-1}$ ),  $Q_0$  is the flow at the beginning of the recession ( $m^3 \text{ s}^{-1}$ ),  $\alpha$  is the coefficient of recession,  $t$  is the time (days) from the beginning to the end of the recession, and  $e$  is the basis of the Neperian logarithm (2.71828).

Thus, the coefficient of recession can be determined numerically, based on the logarithmic form expressed in Equation (5):

$$\alpha = \frac{\text{Log}Q_0 - \text{Log}Q_t}{0.4343t} \quad (5)$$

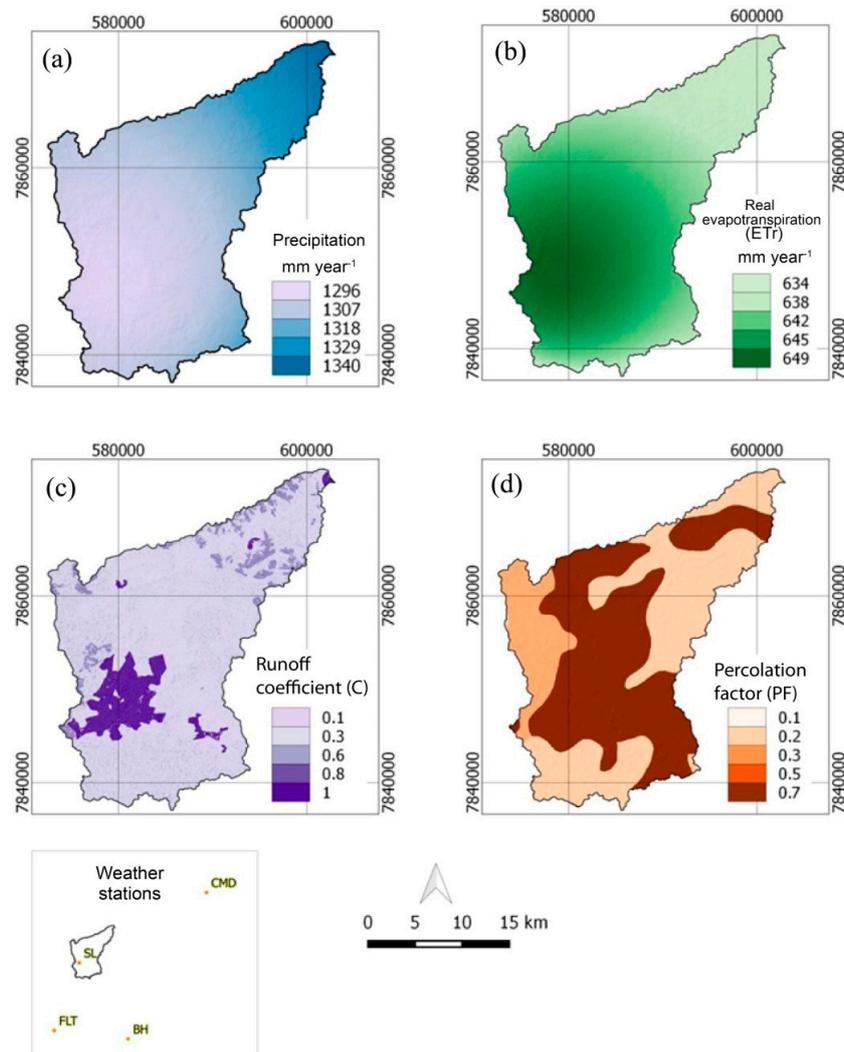
Subsequently, the groundwater recharge volume was calculated using Equation (6):

$$V = Q_0 \times t^* / \alpha \quad (6)$$

where  $V$  is the recharge volume ( $m^3$ ),  $Q_0$  is the flow at the beginning of the recession ( $m^3 \text{ s}^{-1}$ ),  $t^*$  is the unit converter (days to seconds; 86,400), and  $\alpha$  is the recession coefficient (dimensionless).

### 3. Results

The interpolation of climatic data from the rainfall stations in the JRB region (period 2000–2018) showed a variation in average annual precipitation from  $1296 \text{ mm year}^{-1}$  in Sete Lagoas to  $1340 \text{ mm year}^{-1}$  in regions near the river mouth, in the municipality of Jequitiba (Figure 3a). The spatial distribution of the real evapotranspiration was inversely related to the precipitation, presenting  $634 \text{ mm year}^{-1}$  to  $649 \text{ mm year}^{-1}$ , with higher values in Sete Lagoas, and lower values near the headwaters of the drainage area and in the river mouth (Figure 3b). The highest real evapotranspiration in Sete Lagoas can be attributed to the urban area, which waterproofs the soil making the surface water exposed for a longer time, favoring the evaporation rather than the infiltration process.



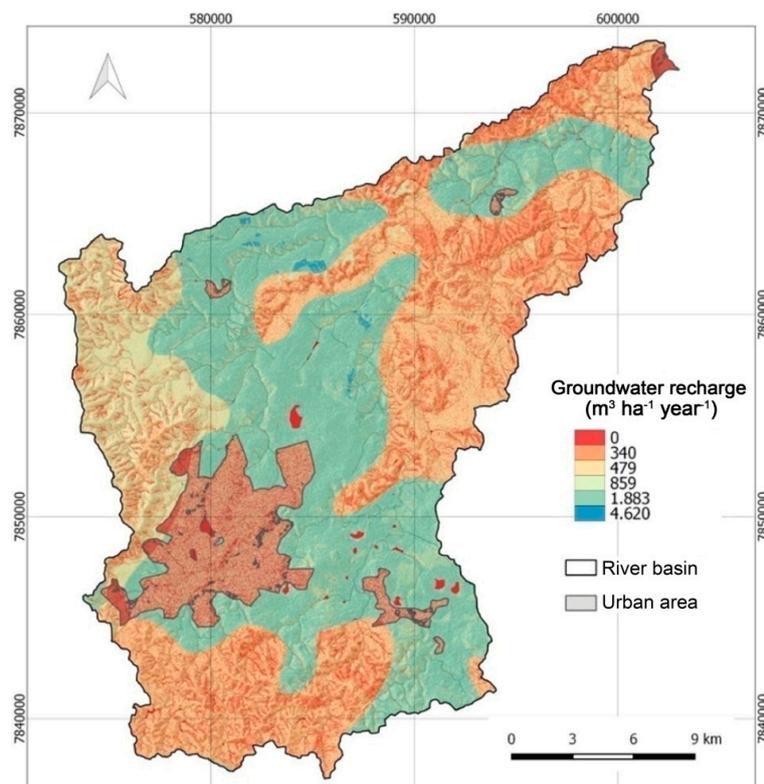
**Figure 3.** Spatialization of hydrological components used to estimate the groundwater recharge potential (Equation (3)) of the Jequitiba River basin, MG, Brazil: (a) Precipitation; (b) real evapotranspiration; (c) surface runoff factor—RF; Equation (1); (d) percolation factor—PF; Equation (2).

The surface runoff (RF) calculated by Equation (1) took into account the land uses (Figure 1c) and associated surface runoff coefficients ( $C$ ; Table 2), as well as the slope length and steepness factor estimated for each point in the Jequitiba catchment ( $LS_{fuzzy}$ ). The calculation of  $LS_{fuzzy}$  resorted to tools embedded in the GIS platform (QGIS), which implement methods that are proper for topographically complex landscape units [88]. The results reveal a strong influence of  $C$  in the values of RF because the largest values of RF (0.8–1.0) occur in the Sete lagoas town where the  $C$  value is the highest (0.85; urban area). The urban densification in Sete Lagoas contributed to a higher surface runoff,

because urban drainage systems prevent storm water from infiltrating into unsaturated parts of the soil (Figure 3c).

The percolation factor (*PF*) calculated by Equation (2) took into account the spatial distribution of soil types (Figure 1b) as well as the corresponding porosities and hydraulic conductivities (Table 3). The percolation factor ranged from 0.1 to 0.7 (dimensionless), expressing the combined variation of soil permeability and total porosity in the area (Figure 3d). The *PF* values are over estimated in the urban area of Sete Lagoas, because the figure does not account for the effects on *PF* caused by compaction and cementation. These overestimated *PF* values produce little impact on the recharge potential (see Figure 4) because the corresponding *RF* values are very low ( $\approx 0$ ).

The mapping of recharge potential (Figure 4) resulted from a combination of maps using the proper tools of QGIS. The input maps were spatial distributions of precipitation, real evapotranspiration, *RF* factor and *PF* factor, illustrated in Figure 3, which were combined on a pixel basis according to Equation (3). The results showed that the groundwater recharge potential of the JRB ranges from 0 to  $4626.4 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , with a mean of  $953.72 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ . The areas with the highest recharge potential are in regions with dense arboreous vegetation cover, flat or slightly undulated relief, and developed and structured soils, whose porosity and hydraulic conductivity allow water percolation to the water table. These areas are concentrated in the south-southeast of the headwaters in Prudente de Moraes, in Sete Lagoas towards the central part of the basin, and between Funilândia and Jequitiba, near the Jequitiba river mouth. The concentrated areas with lower groundwater recharge potential are mainly in Sete Lagoas, due to its urban area, which causes waterproofing of the soil through roofs and pavements (Figure 5).



**Figure 4.** Groundwater recharge potential of the Jequitiba River basin, MG, Brazil.

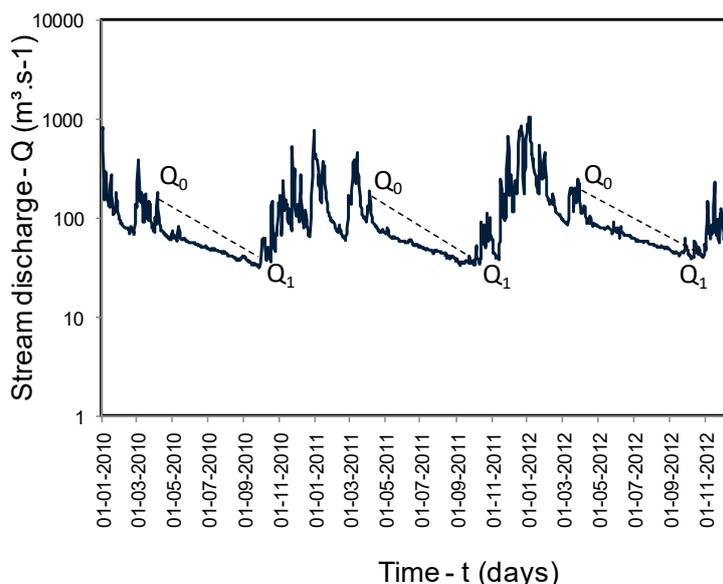


**Figure 5.** Example of waterproofed area in the Jequitiba River basin, MG, Brazil, due to urban areas in the municipality of Sete Lagoas.

The validation of the results indicated that the groundwater recharge volumes obtained by the spatialization of the groundwater recharge potential and that obtained by the analysis of the hydrograph recession were similar, with a relative volumetric difference of 14.4% (Table 4). The hydrograph used to calculate recharge based on stream flow recession is displayed in Figure 6. The recession constant ( $\alpha$ ; Equation (5)) was calculated three times, considering the three recession periods represented in the figure and the corresponding initial discharge ( $Q_0$ ), final discharge ( $Q_1$ ), and recession time ( $t_1-t_0$ ). Then, an average value was used in Equation (6), coupled with an average  $Q_0$ , to obtain the mean recharge potential.

**Table 4.** Groundwater recharge volumes in the Jequitiba River basin, MG, Brazil, estimated by two methods.

Method	Volume (m <sup>3</sup> )	$\Delta V$	$\Delta V$ (%)
Spatialization	$3.63 \times 10^9$	$5.22 \times 10^8$	14.4%
Recession analysis	$3.11 \times 10^9$		



**Figure 6.** Hydrograph of Jequitiba River with indication of  $Q_1$  and  $Q_0$  values used to calculate the recession constant (Equation (5)).

The small difference between the calculated recharge volumes are likely to be related with differences between the two recharge estimation methods. In general, comparison of recharge estimates is difficult because of different levels of unavoidable inherent uncertainty associated with each method [93]. In the present study, the spatialization approach estimates recharge using a water balance equation based on precipitation and evapotranspiration data as well as on spatially distributed topographic, land use, and soil data, while the hydrograph approach estimates recharge using a storage variation equation based on stream flows. The spatialization approach is likely to incorporate larger uncertainty in the recharge values because the number of parameters involved in the calculations is larger. However, the hydrograph approach provides a single (average) recharge estimate while the spatialization approach provides an estimate for each point in the catchment.

It is worth to note that estimation of recharge did not account for differences among aquifer types. It is unlikely that these differences significantly affect the recession based results, because measured stream discharges represent an average flow through all the aquifers. Eventually, aquifers with markedly different characteristics located in specific places within the catchment could influence the water balance based results, because recharge estimation in this case depends on location. The small difference between recession and water balance based recharge values suggest that geology has limited influence on recharge estimation in the studied catchment, and that recharge is likely to be predominantly controlled by infiltration capacity and thickness of soils. The impact of unsaturated zone thickness on recharge has been recently reported in a study in China [94].

## 4. Discussion

### 4.1. Appreciation of Model Results

Information on the characteristics, potential and limitations of each part of a given river basin allows an adequate management in accordance with the demands of the local natural environmental system [95–99]. Thus, although Sete Lagoas has the highest area of the JRB, and soil and relief that favor groundwater recharge, it was behind Prudente de Morais, with an annual average of  $1013.8 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  (Table 5, upper panel). This result was mainly due to its dense population, which leads to waterproofing of the soil. Prudente de Morais presented the highest average annual groundwater recharge potential, with approximately  $1350.8 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  because it is in the part of the basin that concentrates areas with high recharge potential. Capim Branco had the lowest average annual groundwater recharge potential because it has a lower relative area and is in a region with predominance of surface runoff due to steep slopes, and areas with pastures and agriculture.

The average groundwater recharge potentials under the rock classes in the JRB were higher in regions with alluvial sediments ( $1357 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ), colluvial sediments ( $1061 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ), and carbonate and politic rocks ( $829.5 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ) (Table 5, middle panel). These rocks form porous or fractured-karst aquifers, which present great water storage potentials [100]. Lower average annual recharge potentials were found in regions with igneous rocks ( $539 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ), because they are hard, massive, and crystalline rocks, and the water infiltrates mainly through their fractures [101]. The water volume stored in these aquifers depends on the characteristics of cracks in each lithologic type, thus requiring detailed databases that characterize rock fractures in each region.

The average groundwater recharge potential was estimated through the land use and cover map and recharge potential map. According to the results, areas with planted forest had the highest average ( $1899.4 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ) due to their topographic conditions and pedological characteristics (deep and well-structured soils), which are more suitable for forest management (Table 5, lower panel). The highest standard deviation ( $778.5 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ) was also found in these areas, denoting their greater variability. Various studies analyzed the influence of land cover and the benefits of forests for groundwater recharge [102–110].

**Table 5.** Average groundwater recharge potential of each municipality (upper panel), lithologic type (middle panel), and land use (lower panel) of the Jequitiba River basin.

Parameter	Average Recharge Potential ( $\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$ )
<b>Municipality</b>	
Prudente de Morais	1350.8
Sete Lagoas	1013.8
Jequitiba	807.5
Funilândia	633.2
Capim Branco	480.8
<b>Lithologic types</b>	
Alluvial sediments	1357.0
Colluvial sediments	1061.5
Carbonate and pelitic rocks	829.3
Igneous rocks	539.3
<b>Land use and cover</b>	
Forest	1899.4
Agriculture and pasture	888.4
Native vegetation	672.3
Ground vegetation and bare soil	484.0
Urban area	217.1

The average annual groundwater recharge potential of planted forest areas may be different when considering the specific values of maximum evapotranspiration of the crop, physiological characteristics, and management practices. Tree density, root system efficiency to remove soil water, and patterns of stomata opening and closing at certain periods of the year (dry and rainy seasons) and day (morning, afternoon, and night) of planted forests should be considered in further studies to obtain more detailed estimates [111,112]. For example, Leite et al. [113] evaluated water relations in eucalyptus stands and found different patterns for each spacing used and that evapotranspiration of eucalyptus crops with greater spacing between plants is about  $0.91 \text{ mm} \cdot \text{day}^{-1}$  in the dry season, and  $4.48 \text{ mm} \cdot \text{day}^{-1}$  in the rainy season. Other studies related recharge reductions with increasing root depths [114,115].

The average groundwater recharge potential of anthropogenic areas reached  $884.4 \text{ m}^3 \text{ha}^{-1} \text{year}^{-1}$ , with a standard deviation of  $554.1 \text{ m}^3 \text{ha}^{-1} \text{year}^{-1}$ . The areas with natural forest formation had the third highest average annual groundwater recharge potential, reaching more than  $670 \text{ m}^3 \text{ha}^{-1} \text{year}^{-1}$ , with standard deviation of  $481 \text{ m}^3 \text{ha}^{-1} \text{year}^{-1}$ . This difference was due to the topographical and pedological characteristics of the areas. Areas with natural forest formations are different from planted forested areas, and anthropized areas with agriculture or pasture; they have naturally better adaptation to undulated terrain, with steep slopes and shallow soils.

Undulate to mountainous reliefs present native vegetation, which favors groundwater recharge more than areas without well-managed vegetation cover, because the forest reduces runoff and favors water percolation. Thus, forest formations prevent soil losses due to runoff and wind action, maintain soil physical and mechanical stability, and, consequently, assist in water storage and in groundwater supply.

#### 4.2. Controls of Groundwater Recharge and the Need to Delineate Zones of Groundwater Recharge Potential

The karst aquifer of Jequitiba River basin is probably undergoing over-exploitation due to increasing water demand, especially around the Sete Lagoas town where water table decline and suffosional sinkholes are reported for decades. This is enough reason to start an evaluation of groundwater recharge potential, as noted by Arulbalaji et al. [116] while conducting a study for delineation of groundwater potential zones in Southern Western Ghats, India. The methodological approach used in that study was also based on geographic information system (GIS), because it is

rapid and provides first-hand information on the studied topic for further developments. However, the GIS was used to calculate a groundwater potential index as result of an overlay weight analysis, while the approach used in the Jequitiba River basin was physically based. Another study [117] based on a groundwater potential index and involving slope, drainage density, land use, geology, lineament density and geomorphological features from a mountainous region in Nalgonda district, Telangana, India, elected as best suitable areas the pediplains and valleys with minimum slope and sediment filling. Similar results were obtained by Singh et al. [118] in the Deccan Volcanic Province of Maharashtra, India, who further highlighted the predominance of low to medium groundwater potential within the studied basaltic area. Fractured igneous rocks were also the less suited areas as regards groundwater recharge potential in the Jequitiba River basin. Slope was not a major control factor of groundwater recharge, because the Jequitiba catchment is mostly shaped on a region of low slope (is monotonous in this regard). As in our case, geomorphologic parameters such as slope were not able to explain groundwater occurrence within the basement terrain of Keffi Area, North-Central Nigeria [119]. A study developed in the coastal part of Arani and Koratalai River basin, Southern India [120], also based on weighted overlay analysis but validated with hydraulic head and borehole distribution analyses, exposed the negative effects of urbanization on groundwater potential, as we also evidenced in the Jequitiba River basin. The most suited areas in the Arani and Koratalai River basin were used for agriculture, but this was also the predominant land use (>80%). The study of Dar et al. [121] carried out in the Mamundiyar basin (India) and still based on overlay analysis, attributed large weights to geomorphology and drainage density using data from previous works, and consequently identified pediment and pediplains with low drainage density as most suited areas. Land use was given the lowest weight. Overall, the current survey of literature identified the weighted overlay analysis as predominant technique for evaluating groundwater potential. Although easy to apply, this technique relies on the rating and weighting of layers, which is dependent on personal evaluations and therefore subjective. The method used in this study is physically based, and therefore objective. Validation was also lacking in many studies. The study conducted in the Arani and Koratalai River basin validated groundwater potential with hydraulic head data, relating the high potential zones with regions where the hydraulic head surface is flat. In the present study, the average groundwater recharge potential estimated by the spatially distributed method was compared with an average value obtained by the recession flow analysis, with very promising results (14% difference). We are therefore confident on the reliability of our physically based and spatially distributed model.

#### 4.3. Management Considerations

Various recent studies estimated aquifer recharge using spatially distributed methods [122–124]. In most cases, the aim was merely to apply techniques, but other studies used the results as tools for water management. For example, Hund et al. [115], while working in Costa Rica, developed a recharge indicator based on a specific relationship between groundwater recharge and rainfall, which allowed estimating total groundwater recharge for a wet season from previously measured cumulative rainfall. The indicator permitted water managers to assess if a specific year was likely fall into a low recharge category prior to the end of the wet season. This information could then be used to trigger short-term adaptation strategies with the goal to “bank” groundwater while surface water sources are still available in the wet season. In the present study, the spatial information on recharge can also be used to identify areas for water “banking”, namely the areas characterized by lowest recharge potentials.

The recharge potential estimated in the present study refers to natural recharge. The calculated values are likely to be underestimated in the urban area of Sete Lagoas, because the so-called urban component of recharge has not been forecasted and can be much larger than the natural component. In urban areas, there are various new components that must be considered in addition to the natural recharge from precipitation. These include leakages from water supply network and storm water drainage systems, and were reported to be 10 times greater than the natural recharge in a study in

the city of Hyderabad, India [125]. Besides the implications for groundwater resource evaluations, the urban recharge issue is relevant for water quality management because the aforementioned leakages may contain contaminants such as metals or hydrocarbons [126–131], as well as for the geotechnical management of the territory because concentrated infiltration through storm water drainage systems can lead to suffosional sinkhole development in karst areas [132]. Urban and water planners should be made aware of these issues and work together to avoid aquifer recharge through storm water drainage systems, especially in the Sete Lagoas town that is laid over a karst.

The areas used for agriculture and pasture are predominant in the studied catchment and were considered the second most favorable areas for groundwater recharge. It is however necessary to recall that recharge in agricultural areas is largely influenced by irrigation practices. Porhemmat et al. [133] investigated the effects of irrigation methods on potential groundwater recharge and concluded that annual potential groundwater recharge under furrow irrigation was estimated in the range of 19–228 mm, with an average of 111.3 mm. However, mean annual potential groundwater recharge under the sprinkler (4.1 mm) and drip (0.7 mm) was an order of magnitude lower than furrow irrigation. These results raise questions about the sustainability of water-saving irrigation methods, and should be attended by farmers and water planners from the Jequitiba watershed. On the other hand, the practice of furrow irrigation in karst areas is more likely to trigger or accelerate the development of suffosional sinkholes [134,135] with negative consequences for the practice of agriculture.

## 5. Conclusions

The proposed objective was to develop and apply a physically based spatially distributed recharge estimation model in a catchment largely influenced by anthropogenic activities (Jequitiba River, Minas Gerais, Brazil), to serve as water management tool for water planners and policy makers. The results showed areas with greatest potential concentrated in south-southeast regions of the basin and near the river mouth. The groundwater potential was highest in the porous aquifers overlaid by planted forests and lowest in the igneous rocks overlaid by urban areas. Waterproofing was considered a key factor of reduced recharge in the urban area of Sete Lagoas. The adoption of management practices are expected to improve natural groundwater recharge, and hence, significantly increase the available water volume to the local population. Water management initiatives may include seasonal storage of surface water in areas of low recharge potential or adjustment of irrigation methods. Preservation of forest vegetation is also recommended because these areas were considered the most favorable for groundwater recharge. The use of a physically based approaches may be more adequate in the evaluation of groundwater recharge potential, relative to more frequently used weighted overlay analyses, because the former methods are potentially free from subjective steps.

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