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Abacus to Predict Groundwater Recharge at Non-Instrumented Hydrographic Basins

Ronaldo Medeiros dos Santos [1,2,*], Sérgio Koide [2], Bruno Esteves Távora [2] and Daiana Lira de Araujo [2]

[1] Department of Forestry Engineering, Federal Institute of the North of Minas Gerais—Campus Salinas, Salinas 39560-000, Brazil

[2] Department of Civil and Environmental Engineering, University of Brasília, Brasília 70910-900, Brazil; skoide@unb.br (S.K.); bruno.eng.ambiental@gmail.com (B.E.T.); daiana_lira@hotmail.com (D.L.d.A.)

* Correspondence: ronaldo.medeiros@ifnmg.edu.br

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Abstract: One of the first steps to implement a policy for groundwater resources management is knowing the groundwater recharge. However, the unavailability of data and resources to execute field studies increase the uncertainty associated with the estimation of groundwater recharge. To fill this gap, the present work aimed to propose a method to predict groundwater recharge at non-instrumented hydrographic basins. The approach proposed is based on using an abacus to execute the transposition and/or regionalization of results generated in an experimental basin. The methodology comprised the estimation and mapping of recharge rates in the experimental basin using three distinct approaches—numerical modelling of the saturated zone, distributed hydrological modelling of the vadose zone, and the method of fluctuation of the water table elevation—and the following generation of the abacus, with average recharge values for combinations of soil class, land use/cover and slope using geographic information systems. The results indicate that the abacus is consistent for some Ferrasol areas, that the reliability of average regionalized values depends on the complexity of the physical environment—soil class, land use/cover, and slope—and that new studies, focusing on the hydro-physical characterization of soils, might produce more reliable estimations.

Keywords: experimental hydrographic basin; groundwater recharge; regionalization; water resources management

1. Introduction

Despite the importance of groundwater in volume, ecology, economy, and society, the lack of knowledge about hydrogeological systems contrasts with scenarios of contamination and depletion of these systems because of inordinate exploitation [1–3]. Considering that the remediation and/or recovery of aquifers is, at times, unfeasible [3], management is the best alternative to protect and maintain groundwater reserves [3–5]. One of the first steps to implement a groundwater management policy is the knowledge of water availability and for that it is essential to investigate aquifer's renewal rate [6–8].

Rainfall is the main source for groundwater natural recharge, which is regulated by an array of physical and climatic factors, such as geological framework, soil type, slope, vegetation, land cover, and evapotranspiration [9–11]. According to Scanlon et al. [12] and Singh et al. [13], there is no universal approach to study groundwater recharge and that is why the amount of methods reported in scientific literature is high. Amongst these methods, it can be highlighted: (i) the ones based on measuring the water table level [14–16]; (ii) the ones that use chemical tracers [17–21]; (iii) the ones based on direct or indirect measures of hydrological flows, such as baseflow [15,22–24] and water balance [15,25–27]; and (iv) the ones based on hydrological or numerical modelling and/or simulations [27–33].

Quantifying groundwater recharge, however, is a difficult task [13,34,35]. Such difficulty is based on the fact that each method, among those available, may have applicability restricted to certain physical conditions of the study area, such as types of soil or climate, and it can valuate a specific type of recharge, such as potential recharge or effective recharge, or it can be indicated only for punctual estimates [15]. Some methods that use direct flow measures, for example, may generate good results when obtaining point values, but may be infeasible to characterize the spatial variability of the process. On the other hand, distribution methods are disregarded, at times, due to the amount and variety of required data, a demand that is limited precisely by the lack of such data [7,15]. This complexity represents a considerable challenge to quantify the recharge and the only solution to obtain reliable estimates, in many cases, is the combined application of several methods which in turn, would require resources and data not always available [15]. The problem is not restricted to groundwater recharge studies, and a way to overcome it is the transposition or regionalization of the results generated at experimental basins [36]. In such a case, the hydrological monitoring is intensified by adopting a smaller study area, and the selected environment may have physical and environmental characteristics that represent the larger basin or the biome to which the experimental basin belongs. Consequently, the data collected may be used as the foundation for studies that can generate results applicable also for non-instrumented areas with similar characteristics [37]. Lima et al. [38] and Creed et al. [39] used the solution when they adopted an experimental basin to study and comprehend the general hydrological and climatological processes, such as evapotranspiration, surface flow, generation of sediments, and global warming. In groundwater recharge research, Chang and Rubin [36] evaluated the performance of the statistical hierarchical analysis to understand the relationship between hydrological response watershed characteristics, for the regionalization of recharge in ungauged basins and Ibrahim et al. [40] used multiple linear regression to predict recharge in ungauged basins, generated from the relationship between simulated recharge in five gauged basins and their physical and climatic characteristics.

Considering that the groundwater recharge-regionalization remains a non-trivial procedure [36], transferring the results generated at experimental or representative basins still requires scientific efforts, mainly when observing estimations required for undocumented areas where the values adopted are arbitrary or based on studies executed at other areas with completely different characteristics than the study area. In Santos and Koide [41], for example, the simulated recharge rates are higher than 70% of the rainfall in a Cerrado area, while the management institutions and modelling studies in Brazil frequently adopt the average value of 20%, according to Araujo [42]. Recent works have shown the extent of the error that such general assumptions induce, especially when the objective is land use/cover management for water management, because even within the same area, biome, or hydrographic basin, the recharge rate can have wide spatial variations [43].In Bortolin et al. [1], the estimated recharges at a hydrographic basin located in the state of Rio Grande do Sul varied between 9% and 36% related to annual rainfall. The results of Ramires and Manzione [44] indicate a recharge between 20% and 36% at a Cerrado area in the center west of the state of São Paulo. For the same region, Gonçalves and Manzione [7] suggest that the percentage recharge rates do not suffer significative variations in function of the rainfall volume. Silva [45] estimated values with a higher range of variations, between 15% and 50%, also for a Cerrado biome area in São Paulo. In the state of Minas Gerais, Souza et al. [2] simulated and mapped the spatial distribution of recharge rates at the Doce river basin and, for the Ferrasol class, reached results very close to the ones estimated by Cambraia-Neto and Rodrigues [8], close to 30% of the annual rainfall for the same soil type at a basin in the Federal District.

The scientific efforts to comprehend the recharge process would be fruitless if not for the conversion of knowledge in usable data, without which the management stakeholders would hardly fulfil their role regarding the guarantee of universal and sustainable water availability. In this context, scientific works research the relation between urbanization and water quality, between land cover, flow, and sediments, and between vegetation and evapotranspiration, amongst others. Regardless of the issue, the intention, for the most part, is to provide tools for information gathering, in a way that water management may be more rational and efficient. According to Bortolin et al. [1], for surface water a lot has been accomplished in that sense, but there is still a huge gap to bridge when it comes to groundwater.

Charles et al. [46] estimated recharge rates using water balance for several combinations of climate, soil type and land cover. They proposed an electronic spreadsheet to estimate recharge in other sites using the mentioned environmental factors as input data. Although the study with the proposed spreadsheet did not have an experimental basin, it is a case of results transposition, which is useful for the process of integrated water resources management, but hardly used in Brazil. Santos [47] presented, preliminarily, an alternative, however, at the time, there were no published studies that could validate the proposition.

In that sense, the aim of the present work is to propose an alternative method to predict groundwater recharge at non-instrumented hydrographic basins based on the transposition and/or regionalization of the results generated at an experimental basin representative of the Cerrado biome.

2. Materials and Methods

The study area comprised, as the experimental basin, the Capão Comprido basin, located at the west portion of the Federal District, between the west longitude meridians 48°10′07″ and 48°06′13″, and the south latitude parallels 15°43′42″ and 15°45′41″ covering an area of approximately 16 km^2. The Ribeirão Rodeador basin, with 113 km^2, was used to validate the study (Figure 1).

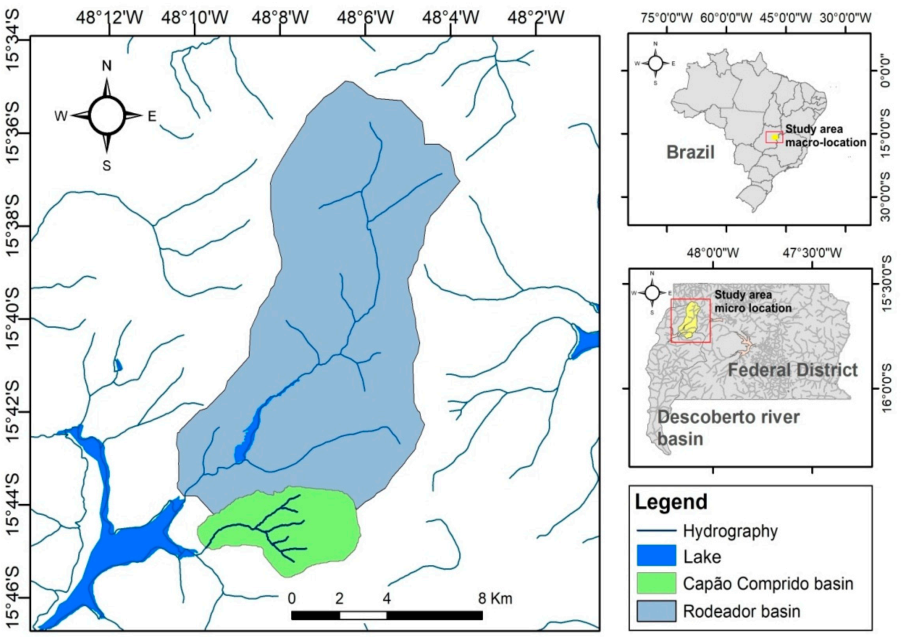


Figure 1. Location of the study area and the validation area.

The two basins are located in the Brazilian Cerrado biome and are under the same climatic domain—Aw humid/sub-humid—with well-defined rainy (spring/summer) and dry (autumn/winter) seasons. Rainfall occurs mainly between October and April, and the average temperatures of the hottest month and the coldest month are 24 °C and 10 °C, respectively. The air relative humidity can reach a critical level of 13%. The annual average rainfall between 1971 and 2016 was 1500 mm [42,47]. Geologically, the same formations of the Paranoá Group are present in both basins—Clay Metarritmito, Medium Quartzites and Sandy Metarritmito [48]. According to Reatto et al. [49], in the Capão Comprido basin the predominant types of soil are Red and Red-yellow Ferrasol, presenting also, in fewer areas, Cambisol, Plinthosol, and Gleysol. In the Ribeirão Rodeador basin, the same soil classes occur, with, however, more occurrence of Cambisols in relation to the Capão Comprido basin, and a small occurrence of Quartzarenic Neosol [42]. Regarding land use/cover, the Capão Comprido basin is predominantly rural, occupied by small farms, with remnants of riparian forests, typical formations of the Cerrado Biome—such as open cerrado grassland, shrub cerrado, and cerrado fields and cerrado—areas under anthropic uses, such as pastures, reforestation, olericulture and perenial/fruit crops, and bare-soil areas. In the Rodeador basin, the majority land use/cover are Annual Crops/olericulture, cerrado fields, open cerrado grassland and reforestation, also occurring small areas of pastures, perenial/fruit crops, riparian forest, bare-soil, and urbanization. Eight land use cover classes are common to both basins: Riparian Forest; Forest/Reforestation; Perenial Tree Culture, Cerrado Fields, Shrub Cerrado, Open Cerrado Grassland, Pasture and Bare Soil [42,47]. The main difference between the two basins, in terms of land use/cover, refers to the Annual Cultures/Olericulture class, with wide distribution in the Rodeador basin, but is not very significant in the Capão Comprido basin.

The materials used in the present work consisted of field data and theme plans of cartography information. The field data, continuously monitored at the study area, comprised historical series of pluviometry, fluviometry, meteorology, piezometry, and hydrogeological information, while the geographic data is constituted of maps of geology [48], soils [49], hydrogeology [48], altimetry from the SICAD-Federal District Cartography System and satellite imagery from the HRV/SPOT5 sensor. The elaboration of models and simulation were executed with the software Visual MODFLOW v.4.2, WETSPA (Water and Energy Transfer between Soils, Plants, and Atmosphere) and IDRISI, Andes version, while the maps were prepared in the software QGIS Desktop 2.18.23.

The methodology comprehended (i) mapping the spatial distribution of the recharge rates using three different approaches, (ii) generation of recharge codes and average recharge values for each possible combination of soil, land use/cover and slope, (iii) and verification of average abacus recharge rates, when regionalized in another area under the same characteristics. The steps are detailed in the following sections.

2.1. Mapping the Spatial Distribution of the Recharge Rates

Considering the lack of direct methods to quantify groundwater recharge and the specificities of the available approaches, the best way to study recharge is to apply at least two different methods, preferably ones that have no correlation [12]. Taking into account the aims of the present work, distributed methods were selected and applied. These methods are capable of generating not only estimations, but also spatially characterizing the recharge process. In that sense, three approaches were proposed: numerical modelling of the flow in saturated porous medium (MODFLOW); hydrological modelling of the vadose zone (WETSPA); and spatialization of point estimations calculated using the water table elevation (WTE).

2.1.1. Numerical Modelling of the Saturated Zone

This approach comprehended the elaboration of a numerical hydrogeological model of the phreatic aquifer at the study area, which was used to simulate groundwater flows and recharge via vertical and horizontal numerical simulation, using finite difference cells at the Visual MODFLOW v.4.2 software. The modelling contained the following reasoning: (a) recharge is one of the processes responsible for the alteration of the condition of the aquifer system over time and there are no measured values for the recharge processes at the study area; (b) however, the "fixed" characteristics of the system (structural configuration and properties of the aquifer's material) and the temporal variations of its behavior (storage and phreatic level) are known, as well as other correlated measurable factors (evapotranspiration and surface water overflow); (c) thus, recharge is the unknown variable to be found. Since recharge is usually an input data, the problem can be solved with reverse modelling. Therefore, spatial distribution and recharge rates were estimated using calibration. The methodology developed, summarized in Figure 2, is more detailed in Santos [47] and Santos and Koide [41].

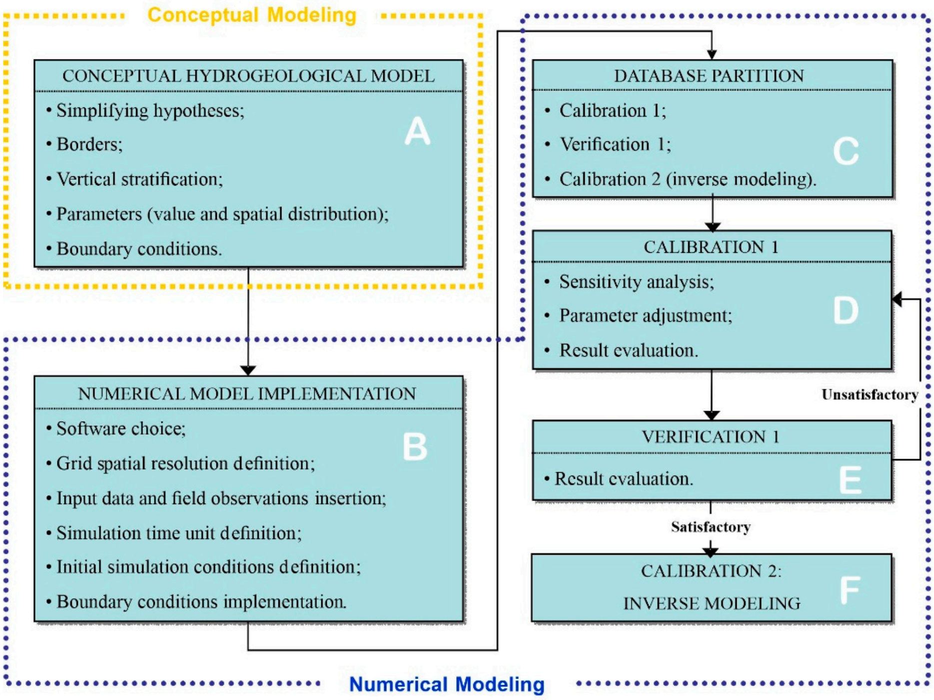


Figure 2. Steps of the numerical modelling method (**A**: items of the conceptual hydrogeological model, **B**: steps of the numerical model implementation, **C**: database partition between modeling steps, **D**: steps of the calibration process, **E**: calibration process evaluation, **F**: recharge estimation by inverse modelling) [41,47].

2.1.2. Distributed Hydrological Modelling of the Vadose Zone

This step was based on applying the model WETSPA—Water and Energy Transfer between Soils, Plants, and Atmosphere [50]. It is a physically based distributed model with routines to simulate water flow between the atmosphere, vegetation's canopy, root zone, transmission zone, and saturation zone, as illustrated in Figure 3.

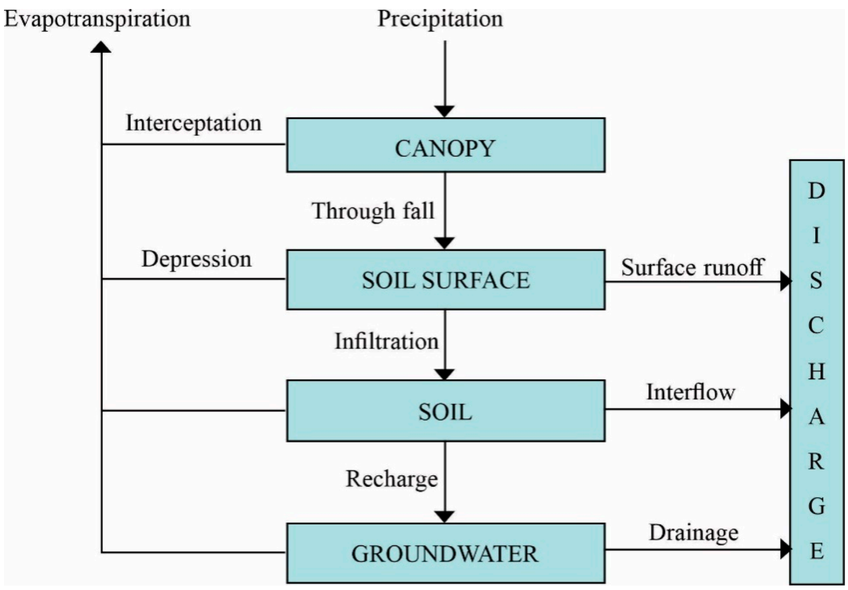


Figure 3. Hydrological processes and WETSPA (Water and Energy Transfer between Soils, Plants, and Atmosphere) model structure [50].

Using basic maps of slope, soil types, and land cover, this model executes the mapping of parameters spatial distribution in geographic information systems. The parameters modelled are related to water storage and movement through physical compartments, such as field capacity, permanent wilting point, hydraulic conductivity, surface water flow coefficients, leaf area index and Manning coefficient, amongst others. The mapping is based on linking spatial information in the basic maps with tables with parameters values, indicated in function of constant values or classes in the maps. Then, using the spatially distributed parameters, the measured data of average rainfall and the estimated values of potential evapotranspiration, the algorithm simulates the hydrological processes, including recharge, for each cell in the model. The daily total surface flow at the basin discharge point, estimated using the discharge rating curve, was used as a control observation in the calibration and verification steps. The complete formulation of the model is detailed in Santos [47] and Liu and Smedt [50].

2.1.3. Spatialization of Point Estimations Calculated Using Water Table Level Elevation

Having the monitoring data of the phreatic level, the piezometric elevations resulting from the recharge period during the rainy season were estimated. The elevations observed in each monitoring well were obtained graphically, measuring vertical distance between the maximum piezometric head and the prolongation of the recession line of the piezometric curve, a method indicated by Healy and Cook [51]. The point recharge, valid for the monitoring well's influence area where the phreatic elevation was measured, was estimated by multiplying the total elevation, in mm/year, by the aquifer's local value for the specific productivity coefficient, Sy. The values for Sy were obtained using a pumping test and a slug test, performed by Santos [47], in the monitoring wells at the Capão Comprido basin.

The spatial distribution of the recharge was obtained using a model for spatial multiple regression, of the type "Y = a + b1X1 + b2X2 + b3X3 + ··· + bnXn", placing the point estimation in the dependent variable (Y) in relation to the spatial distribution of the predefined factors (X1, X2, X3, . . . Xn) that are determining to the process (terrain slope, land cover and use, hydrodynamic behavior of the aquifer, aquifer width, and phreatic depth, in this work). Since the order of magnitude and the unities of the mentioned factors are different, the respective normalized maps were used. More details about the method proposed in this step is described in Santos [47].

2.2. Generation of Recharge Codes and Average Recharge Values for Possible Combinations between Soil, Land Use/Cover, and Slope

Based on the principle which states that groundwater recharge is a result of the combination of "fixed" environmental factors, it can be expected that areas in the same biome or geographic region will have predictable hydrological behavior regarding the conversion of rainfall in groundwater at the aquifer. Identifying the possible combinations of such factors and quantifying the recharge for the mentioned conditions in representative sites or basins, it is supposed to be possible to estimate the unknown variable for non-instrumented areas that have the same combination of considered environmental factors. In this sense, the last step comprised of mapping the spatial distribution of the combinations of factors related to recharge, and the intersection of this map with the spatial distribution of the recharge rates generated in previous steps of the present work.

In the first procedure, based on the conceptual proposed by Santos [47], were considered the factors "soil class", "land use/cover", and "slope". Unique identification numbers were attributed to the classes or variations from each factor in the following way:

- soil class: 1 = cambisol; 2 = red-yellow ferrasol; 3 = gleysol; 4 = red ferrasol; 5 = plinthosol;
- land use/cover: 1 = riparian forest; 2 = forest/reforestation; 3 = perennial tree culture; 4 = cerrado fields; 5 = shrub cerrado; 6 = open cerrado grassland; 7 = pasture; 8 = baresoil;
- slope: 1 = slope between 0 and 5%; 2 = slope between 5 and 10%; 3 = slope between 10 and 15%; 4 = slope over 15%;

The maps related to each factor were converted to vector format and the data crossing was performed by an intersection operation, both spatial and of attribute, resulting in polygons with unique three digits identification numbers representing the physical conditions of the site. Lastly, it was executed by a spatial intersection, using a zone operation between the polygons with the combination of factors and the spatial distribution of recharges, thus obtaining an abacus, with which it is possible to estimate, for each combination of type of soil, land cover and slope, the average values of simulated recharge, considering the three aforementioned methods.

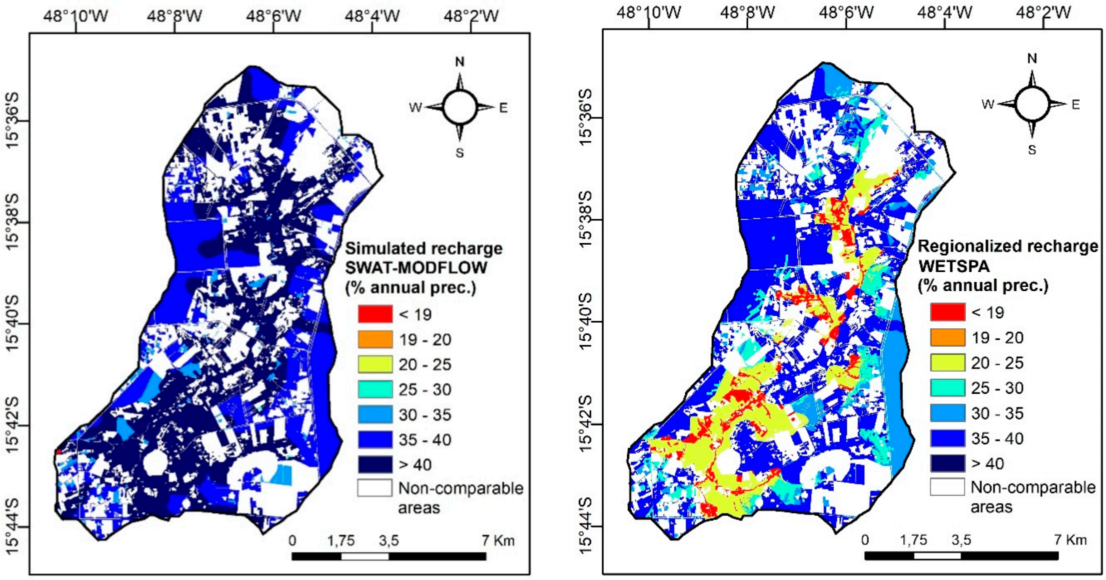
2.3. Verification of Average Abacus Recharge Rates

The validation of the average estimation of recharge in function of the combination of physical and environmental factors was performed using the abacus at another area in the Cerrado biome. Using the maps of type of soil, land cover/use, and slope of the validation basin, new maps were generated with the combination and the respective codes. Lastly, applying the abacus to the map and recharge codes of the validation basin, transposed/regionalized values for the recharge were obtained, which were confronted with the estimations generated by Araujo [42]. In this research, the spatial distribution of the recharge rates was obtained through integrated hydrological modeling of surface and saturated zone processes. The model used was the SWAT-MODFLOW [52], a tool that integrates the models SWAT (Soil and Water Assessment Tool) and MODFLOW. The model input was the time series of meteorological, precipitation, discharge and water table data, physical digital cartographic information of the basin (soil map, digital elevation model and land use/cover) and geological and hydrodynamic information for the saturated porous medium (spatial distribution of saturated hydraulic conductivity and specific yield and vertical stratification of the model domain). The discharge, base flow and water table level data refer to the hydrological year 2008/2009—the same time period adopted in the generation of the abacus—were used for model calibration and verification. The recharge simulated by this method is "potential", as the abacus recharges obtained by the WETSPA model. The other results of the abacus—MN and WTF, of effective recharge—were evaluated by comparison with average values of effective recharge found in the literature.

3. Results and Discussion

The present work mapped 85 possible combinations of type of soil, land use and slope at the Ribeirão Rodeador basin. The average values for the simulated recharge in Araujo [42] are presented on the map in Figure 4a. Figure 4b presents the regionalized values from the abacus application. For some areas in the Rodeador basin it was not possible to map and compare the values due to the existence of combination between factors that are not present in the Capão Comprido basin, used to formulate the abacus. The recharge rates estimated by the methods "Numerical Modelling—NM" and "Water Table Elevation—WTE" were not included in the comparison, because they perform "effective recharge" estimations [8,41] and, consequently, give lower estimations than the ones obtained with the vadose zone methods, such as SWAT-MODFLOW and WETSPA.

According to the results simulated by Araujo [42], the average recharge rates varied between 20% and 60% of the total annual rainfall (316.2 and 948.6 mm/yr, based on the rainfall of the hydrological year 2008/2009, of 1581 mm), with higher values associated with types of soil Cambisol, Red-yellow Ferrasol, Plinthosol, and Gleysol. It was also observed the influence of the slope on the groundwater recharge process, that is, the recharge rates are low when the slope is high, in a same type of soil. For the regionalized values, the recharge rates were lower, in general, and the rates increased, presenting the higher values, when associated with deep soils, such as Ferrasols and Plinthosols, in low slope areas. This behavior in function of the individual variables of the factors "soil class", "land use/cover", and "slope" is synthetized on Figure 5.



(**a**) (**b**)

Figure 4. (**a**) Spatial distribution of the simulated recharge; (**b**) Spatial distribution of the regionalized recharge.

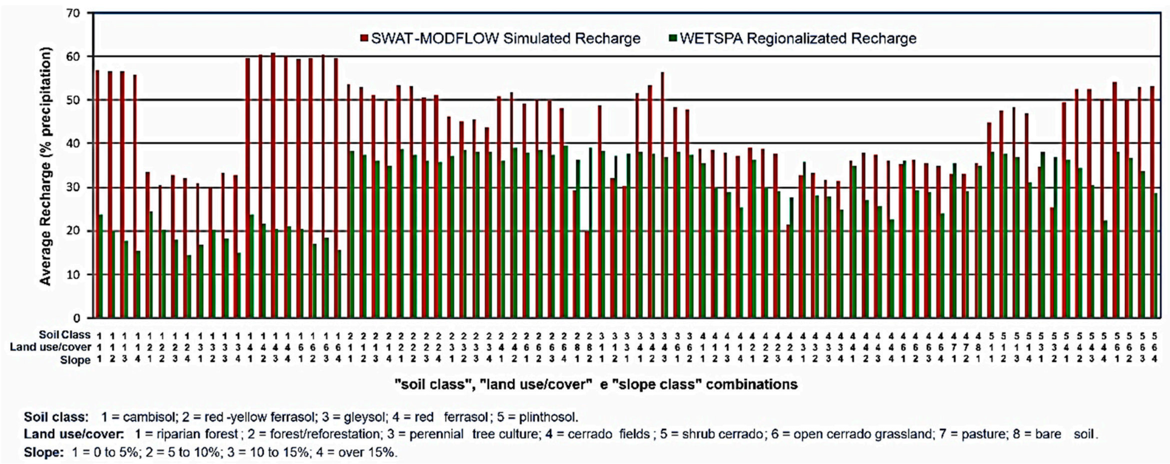


Figure 5. Behavior of the recharge in function of the factors "soil class", "land use/cover", and "slope".

Despite the difficulty of analyzing separately the influence of each factor [36], it was observed that the recharge varies according to the type of soil—between 35% and 48% in the simulated average rates per class and between 19% and 38% in the regionalized rates averages per class. However, depending on the class, land use/cover may have a major or minor influence than the soil, as, for example, in the case of Cambisols and Red Ferrasols, respectively. In the former, the type of land use/cover caused average rates between 30% and 60%, while in the latter, the variation observed between rates was lower, with values between 32% and 38%, for the simulated rates. Considering the differences between the approaches, a greater influence of the type of soil is observed, followed by the declivity and land use, which can be better visualized by mapping the relative error and spatially comparing it with each factor analyzed (Figure 6), and by observing the results from Table 1: a preliminary abacus, through which recharge rates can be regionalized in non-instrumented hydrographic basins for combinations of soil class, land use/cover, and slope factors. Estimations with low relative error can be considered more reliable [15,35].

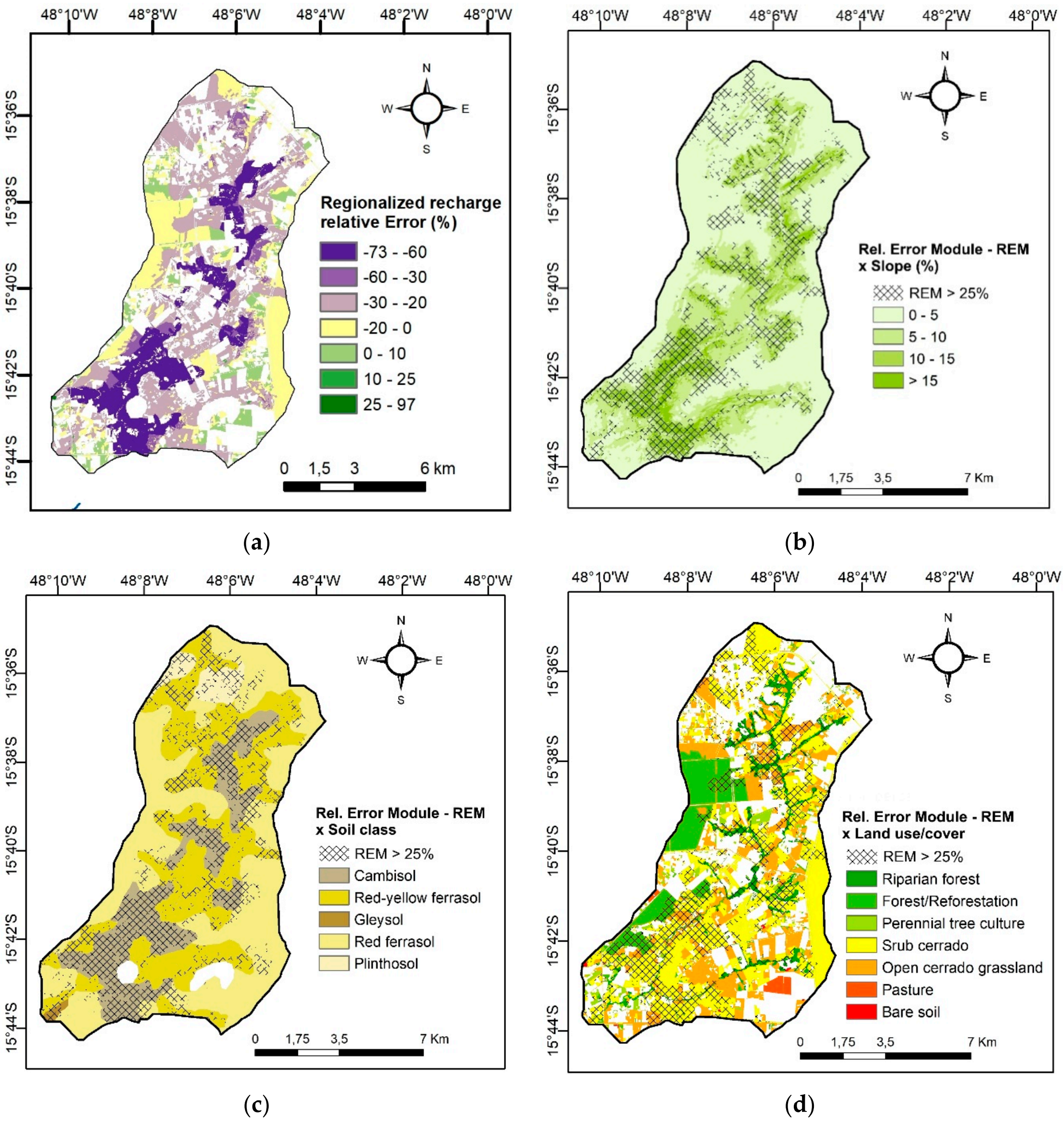


Figure 6. (**a**) Relative error of the regionalized recharge and its relation with the factors (**b**) "slope", (**c**) "soil class", and (**d**) "land use/cover".

Table 1. Potential recharge rates for each combination of "soil class", "land use/cover", and "slope" for the Cerrado Biome in the Federal District.

Code	Simulated Recharge SWAT-MODFLOW (% Annual Prec.)	Regionalized Recharge WETSPA (% Annual Prec.)	Relative Error (%) SWAT-MODFLOW "Versus" WETSPA
111	56.96	23.74	−58.33
112	56.65	19.86	−64.93
113	56.86	17.76	−68.76
114	55.84	15.39	−72.43
121	33.50	24.32	−27.40
122	30.38	20.20	−33.52
123	32.83	17.95	−45.32
124	32.10	14.49	−54.84
131	30.95	16.77	−45.81
132	30.07	20.20	−32.82
133	33.29	18.11	−45.59

Table 1. *Cont.*

Code	Simulated Recharge SWAT-MODFLOW (% Annual Prec.)	Regionalized Recharge WETSPA (% Annual Prec.)	Relative Error (%) SWAT-MODFLOW "Versus" WETSPA
134	32.80	14.97	−54.36
141	59.82	23.78	−60.24
142	60.55	21.73	−64.11
143	60.92	20.54	−66.28
144	59.93	20.83	−65.25
161	59.54	20.44	−65.67
162	59.86	16.90	−71.77
163	60.42	18.33	−69.65
164	59.85	15.60	−73.93
211	53.63	38.36	−28.47
212	53.06	37.45	−29.41
213	51.09	36.00	−29.53
214	49.67	34.85	−29.82
221	53.58	38.80	−27.58
222	53.19	37.36	−29.76
223	50.68	35.97	−29.02
224	51.16	35.77	−30.09
231	46.22	37.12	−19.68
232	45.15	38.72	−14.24
233	45.61	38.12	−16.41
234	43.80	38.21	−12.76
241	50.94	36.15	−29.04
242	51.95	39.18	−24.58
261	49.30	38.00	−22.92
262	50.07	38.70	−22.71
263	49.71	37.33	−24.90
264	48.16	39.59	−17.81
281	29.27	36.30	23.99
282	19.86	38.96	96.11
311	48.88	38.46	−21.33
312	32.19	37.19	15.51
331	30.26	37.75	24.74
341	51.69	38.11	−26.26
342	53.40	37.63	−29.53
343	56.54	36.89	−34.76
361	48.26	38.23	−20.79
362	47.89	37.46	−21.78
411	38.94	35.50	−8.83
412	38.69	29.66	−23.33
413	37.80	28.95	−23.41
414	37.14	25.27	−31.97
421	39.15	36.39	−7.05
422	38.93	29.82	−23.39
423	37.67	29.03	−22.93
424	21.51	27.74	28.99
431	32.84	35.86	9.20
432	33.22	28.21	−15.09
433	31.70	27.94	−11.85
434	31.40	24.92	−20.63
441	35.98	34.97	−2.79
442	37.97	26.93	−29.08
443	37.47	25.59	−31.70
444	36.05	22.63	−37.24
461	35.25	36.11	2.45
462	36.22	29.31	−19.08
463	35.52	28.76	−19.03

Table 1. *Cont.*

Code	Simulated Recharge SWAT-MODFLOW (% Annual Prec.)	Regionalized Recharge WETSPA (% Annual Prec.)	Relative Error (%) SWAT-MODFLOW "Versus" WETSPA
464	34.85	23.97	−31.20
471	33.12	35.62	7.54
472	32.99	29.18	−11.55
481	35.49	34.84	−1.84
511	44.93	38.12	−15.15
512	47.58	37.69	−20.79
513	48.29	36.86	−23.67
514	46.96	31.10	−33.76
531	34.65	38.03	9.74
532	25.29	37.02	46.39
541	49.56	36.20	−26.97
542	52.67	34.51	−34.48
543	52.60	30.51	−41.98
544	50.14	22.31	−55.49
561	54.13	38.25	−29.33
562	49.97	36.81	−26.34
563	53.12	33.62	−36.72
564	53.16	28.61	−46.19

The average relative error was −27.5, with the highest values occurring in steeper areas with Cambisol, and some areas with Red-yellow Ferrasol and Plinthosol covered with trees along the drainage network. In those areas, that correspond to circa 29% of the basin area, the relative errors modules of the regionalized rates were higher than 25%—a limit reference value of performance for the statistical index PBIAS [53]—reaching 96% (this extreme error value occurred in an area of about 3 hectares; less than 1% of the total area of the validation basin). It can be highlighted that the mentioned combinations of physical factors are spatially correlated and correspond to configurations of high physical complexity, to which the hydrological models are still limited. In the other areas, the average relative error was −19%.

The model SWAT is a respectable reference when it comes to hydrological modelling. Such status is due to the good performance of the model, mostly to simulate flow rates, exemplified by the countless works developed over the last 20 years in a variety of environments [32]. Nonetheless, Araujo [42] and Arroio Junior [54] emphasize that the model still presents some limitations that may compromise the consistency of the water balance, even if the simulated flow rates are well adhered to the measured flow rates. A good example of these limitations is the lack of reliable parameters for forested steep lands, which frequently results in inconsistencies in the simulation of subsurface flow [54], and another example is the underestimation of the evapotranspiration, that may lead to the overestimation of surface flow rates or recharge rates.

Analyzing the hydrological behavior of five hydrographic basins, Arroio Junior [54] faced the issue of identifying variations amongst the simulated actual evapotranspiration and the measured reference values. After modifying the routine to calculate evapotranspiration, there was a significant reduction in recharge in the five basins.

Despite the discussion about the limitation of the model SWAT-MODFLOW, the results obtained by Araujo [42] indicate that the model's recharge estimations are more reliable. In this model, the simulation of surface and groundwater flows are integrated, exploring the strengths from each original model—SWAT simulating surface water flow and MODFLOW simulating groundwater flow—thus making the global modelling more robust to represent every flow in the hydrographic basin [55]. Using the integrated model, Araujo [42] compared simulated flow rates with measured flow rates, obtaining satisfactory results for the performance indexes, which indicate SWAT-MODFLOW model's ability to represent the hydrological processes in a Cerrado environment. However, the model tends to overestimate baseflow, which could indicate the overestimation of the recharge. Notably, that could happen in steeper areas with Cambisol, where the rates simulated by SWAT-MODFLOW were higher than in other types of soil in the basin and overcame in more than 100% the regionalized rates generated by WETSPA model.

On the other hand, Santos [47] demonstrates the overestimation of recharges due to the underestimation of baseflows in the period used to generate the reference values. Even if comparative studies, such as Nossent et al. [56], reveal an equality in both model's performance when applied to the simulation of hydrological processes in hydrographic basins, WETSPA model's performance was not satisfactory on the case study that generated the reference values.

Then, which recharge rates are indicated? According to Polanco et al. [57], a common limitation in hydrological modelling is the calibration and assessment of results based only in outflow rates. In such cases, a satisfactory statistical performance does not guarantee the consistency of values simulated for water balance nor hydrological processes at the local scale. In that sense, it is cautiously advised to adopt intermediary recharge rate values, between the overestimated ones generated by SWAT-MODFLOW and the underestimated regionalized ones.

For the Cambisol class (number "1", first digit), the great variation between simulated and regionalized values suggest caution when adopting a mean reference value since, according to Castro [58], this type of soil has a wide range of hydrological behavior, which would cause the difference to be actually from real physical variations in the basins. Nonetheless, it can be highlighted that Cambisol in the Ribeirão Rodeador basin is located, predominantly, in steeper areas with Cerrado fields and riparian forests, a combination that, according to Bortolin et al. [1] and Santos [47], is theoretically unfavorable to recharge groundwater.

The estimations obtained for the Red-yellow Ferrasol class (number "4", first digit) were considered more reliable because, in general, they presented the lowest differences. Furthermore, the spatialized values simulated with SWAT-MODFLOW [42] and regionalized with WETSPA in the abacus, which varied between 32% and 39% and between 32% and 36%, respectively, were situated close to the ones obtained by Cambraia-Neto and Rodrigues [8], of 31%, related to annual rainfall for the same physical conditions of soil type, land use and slope in another hydrographic basin located in the east portion of the Federal District. Souza et al. [2] also attained percentage recharge rates of the same order of magnitude, of 36%, for Red-yellow Ferrasol in the Rio Doce basin, west of the state of Minas Gerais. However, in this case the rates of the same order of magnitude for Ferrasols were obtained in different environmental conditions (biome and climate), indicating a dominance of the "soil class" factor in the recharge process and that the role of this factor may be a good variable to use in recharge rate regionalization.

Regarding the effective recharge, the average rates for combinations of soil, land use/cover, and slope have been converted into weighted average rates, by the area factor, for the basin. The average values suggested by the abacus and the reference values obtained in the literature are shown in Table 2.

The average effective recharges suggested by the abacus are smaller than the potential simulated and regionalized recharges, corroborating Gonçalves and Manzione [7] and Healy and Cook [51] regarding the expected difference between the two types of recharge. In comparison to the reference values, the suggested effective rates were considered consistent, in the same order of magnitude as the general average of the rates reported by the mentioned works. It is important to highlight that the study area adopted by Cambraia-Neto and Rodrigues [8]—eastern region of the Federal District—is relatively close to the abacus generating basin, and that the effective average rate of Araújo [42]—19%, is equal to the average of the abacus, also obtained by numerical modeling—it was obtained in the validation basin. The high upper limit of the recharge rates obtained in Oliveira et al. [62] is because the soil in your study area is a highly permeable sandy Quartzarenic Neosol. Thus, the regionalization of the recharge rates proposed by the abacus would only be possible if the study basin has at least the three predominant classes of soil in the Capão Comprido basin—Red Ferrasol, Red-yellow Ferrasol and Cambisols—as occurs in Gaspar [59], Albuquerque and Chaves [60], Cunha [61], ANA [64], Gonçalves and Manzione [7], and Cambraia-Neto and Rodrigues [8].

Table 2. Regionalized average effective recharge rates and average literature reference values obtained for similar environmental conditions (Cerrado Biome).

Abacus Average Effective Recharge (% prec.)	Method	Average Reference Values (% prec.)	Method
15	WTE	15–25 [59]	WTE
19	NM	20 [60]	Baseflow
		17 [61]	Baseflow
		26–30 [62]	WTE
		16 [63]	Baseflow
		17 [63]	Baseflow
		19 [42]	NM
		16 [7]	WTE
		24 [8]	Baseflow
		27 [8]	WTE
Average = 17		Average = 20	

4. Conclusions

The present work proposed an abacus to predict groundwater recharge at non-instrumented hydrographic basins elaborated from the results obtained at an experimental basin in the Cerrado biome. Confronting the proposed values to the ones available in scientific literature and estimated by Araujo [42], for a hydrographic basin with the same environmental conditions, it can be concluded that:

- the potential recharge varies according to the soil class. However, in the same type of soil, land use/cover and slope can cause large variations in recharge rates;
- for combinations between Cambisols and high slopes, the differences between simulated and regionalized potential recharge rates are high, indicating, in this case, caution on the adoption of values suggested by the abacus. As the calibration and verification of hydrological models are proceeds at the basin or sub-basin level, it is necessary to perform site specific studies to confirm the recharge rate actual order of magnitude;
- for soils with more homogeneous porous matrix, such as Ferrasol, the difference between simulated and regionalized rates was smaller, indicating greater reliability on the values suggested by the abacus for such situations;
- the regionalized values of potential recharge suggested by the abacus for combinations with Ferrasols were considered consistent, with order of magnitude confirmed by Cambraia-Neto and Rodrigues [8] and Araujo [42]. Thus, for these combinations, the suggested values can be transferred to other areas or basins in the Cerrado biome with similar characteristics. Similar values estimated by Souza et al. [2] for this type of soil, but with different climate and biome, suggest that the abacus values for Ferrasols may also be valid for other Brazilian biomes;
- the divergences between simulated and regionalized estimations observed in areas with the same soil type, land cover and slope are a result of the conceptual and mathematical formulations specific in the models used, mostly regarding the calculation of actual evapotranspiration, which confirms Araujo [42] and Arroio Junior [54];
- the average effective rates of recharge—NM and WTE—suggested by the abacus were considered consistent, with values in the same order of magnitude as the reference values in the literature. However, the regionalization of these recharge rates would only be possible if the study basin has at least the three predominant classes of soil in the Capão Comprido basin—conditions in which the abacus was generated;

- new studies could produce a more robust abacus. In this sense, it is recommended to focus on the hydro-physical characterization of the soil types, which would enhance the range and reliability of future regionalization of proposed values;
- for non-instrumented basins with physical characteristics similar to the study area, also used to validate the results, the abacus could be an useful tool for surface and groundwater resources integrated management, since the recharge rates can be obtained in an easier way, just by knowing annual average rainfall, land use, soil type, and slope of the new study area, which are data relatively easy to obtain.

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