Hydrogeology Journal
https://doi.org/10.1007/s10040-023-02612-x

REPORT

Assessment of aquifer recharge and groundwater availability in a semiarid region of Brazil in the context of an interbasin water transfer scheme

Alexandre C. Costa[1,2] · Fanny Dupont[3] · George Bier[4] · Pieter van Oel[2] · David W. Walker[2] · Eduardo S. P. R. Martins[5]

Received: 19 April 2022 / Accepted: 7 February 2023

Abstract

Particularly in arid and semiarid areas, more and more populations rely almost entirely on imported water. However, the extent to which intentional discharge into transiting riversystems and unintentional leakage may be augmenting water resources for communities along and down gradient of the water transfer scheme has not previously been subject to research. The objective of this study was to assess both the potential of a large-scale watertransfer (WT) scheme to increase groundwater availability by channel transmission losses in a large dryland aquifer system (2,166 km²) in Brazil, and the capability of the receiving streams to transport water downstream under a prolonged drought. An integrated surface-water/groundwater model was developed to improve the estimation of the groundwater resources, considering the spatio-temporal variability of infiltrated rainfall for aquiferrecharge. Aquifer recharge from the WT scheme was simulated under prolonged drought conditions, applying an uncertainty analysis of the most influential fluxes and parameters. The annual recharge (66 mm/year) was approximately twice the amount of water abstracted(1990–2016); however, the annual recharge dropped to 13.9 mm/year from 2012 to 2016, a drought period. Under similar drought conditions, the additional recharge (6.89 × 106 m³/year) from the WT scheme did not compensate for the decrease in groundwater head in areas thatdo not surround the receiving streams. Actually, the additional recharge is counteracted by a decrease of 25% of natural groundwater recharge or an increase of 50% in pumping rate; therefore, WT transmission losses alone would not solve the issue of the unsustainable management of groundwater resources.

Introduction

Particularly in arid and semiarid areas of the world, more and more populations rely almost entirely on imported water (Davies et al. 1992). Despite their generally large engineering challenges and correspondingly high costs, interbasin water transfer schemes are becoming increasingly common and are increasing in ambition (Rollason et al. 2021). The largest future water transfer mega-projects are located in North America, Asia, and Africa with predicted total investment exceeding US$2.7 trillion (Shumilova et al. 2018). The scale of these supply-oriented solutions attests to the perceived magnitude of the needs and interests of the recipient economic centres (Gupta and van der Zaag 2008).

While there are many examples of water transfers that have brought socio-economic benefits to both the recipient and donor basins, studies are not uncommon in the literature describing negative impacts on donor and transit basins, particularly on marginal communities, who have surrendered rights to land and water (Rollason et al. 2021). However, the extent to which intentional discharge into transiting river systems and unintentional leakage may be augmenting water resources for communities along and down gradient of water transfer schemes has not previously been subject to research. These water transfer losses are of critical importance to water managers and may represent an unexpected windfall

---

✉ Alexandre C. Costa
cunhacos@unilab.edu.br

[1] University of International Integration of the Afro-Brazilian Lusophony, Institute of Engineering and Sustainable Development, Redenção, Brazil

[2] Water Resources Management Group, Wageningen University, Wageningen, The Netherlands

[3] Antea Group, Environment Division, Antony, France

[4] Soil Physics and Land Management Group, Wageningen University, Wageningen, The Netherlands

[5] Research Institute of Meteorology and Water Resources, Fortaleza, Brazil

for local stakeholders. Such investigations are particularly relevant in arid and semiarid areas where managed aquifer recharge (MAR), exploiting existing underground storage and negating evaporation losses, is often promoted as a solution to water scarcity (Dillon et al. 2019).

The semiarid northeastern Brazil (NEB) is a large dryland (982,566 km^2) characterized by annual precipitation levels ranging from 400 to 800 mm, and evaporation levels reaching over 2,000 or 3,000 mm in some areas (Campos 2015). Because of these natural dry conditions and increasing water demand, NEB is regularly confronted with water insecurity issues, which is aggravated by recurrent droughts, i.e., consecutive years of low precipitation (Gutiérrez et al. 2014).

To help distribute water resources more equally within NEB, an interbasin water transfer scheme has been designed by the Brazilian Federal Government. This project aims to transport water from the São Francisco River (SFR) to several intermittent rivers and reservoirs in the states of Ceará, Rio Grande do Norte, Paraíba and Pernambuco (Ministério da Integração Nacional 2004; Lima 2005; Tortajada 2006). SFR is a perennial allogenic river that begins its course in a water-rich region of Southeast Brazil before flowing through the southern part of NEB. SFR discharge represents 3.7 times the surface runoff of the receiving region.

In the state of Ceará, the Salgado watershed is the recipient hydrologic basin of the SFR's water. This watershed contains the major groundwater resources of the state, where groundwater is abstracted by pumping wells for drinking water, irrigation, industry and leisure. However, environmental changes, such as the drying up of creeks and permanent vegetation changes, have been reported due to unsustainable groundwater abstraction rates (Mendonça et al. 2005). The Water Agency of the state of Ceará (COGERH) estimated that the amount of groundwater extracted is much larger than the mean annual recharge (Governo do Estado do Ceará 2011).

Therefore, the receiving rivers from the SFR water transfer flow through an overexploited groundwater region in Ceará. While studies have been focused on the potential environmental and social impacts of such water transfer projects in Brazil (MI 2004; Caúla and Moura 2006; Henkes 2014), none of them has yet studied their potential influence on groundwater availability due to aquifer recharge by channel transmission losses (Costa et al. 2012, 2013). These losses can play an important role in the recharge of the groundwater resources in the Salgado watershed, as losing streams often occur in such areas in northeast Brazil.

The objective of this study was to assess both the potential of the SFR water transfer to increase local groundwater availability in the Salgado watershed by channel transmission losses, and the capability of the receiving streams to transport water downstream under a prolonged severe drought. First, an integrated modelling approach was developed to improve estimations of the groundwater resources in this watershed, taking into account the spatio-temporal variability of infiltrated rainfall for aquifer recharge. Then, SFR water transfer for aquifer recharge was simulated under prolonged drought conditions, considering an uncertainty analysis on simulated groundwater recharge and estimated pumping rates, and a parameter sensitivity analysis of the calibrated groundwater flow model.

Study area

The Salgado River watershed (Fig. 1) covers an area of 12,900 km^2, with a population of about 870,000 inhabitants distributed over 23 municipalities in the state of Ceará, Brazil (IBGE 2012). Intra-annual rainfall variability is distributed in two distinct periods in the watershed: a wet season from January to May with over 70% of mean annual rainfall, and a dry season from June to December. Mean annual precipitation is 920 mm (Golder-Pivot 2005), and potential annual evapotranspiration is 1,566 mm (Costa et al. 1998).

The Araripe sedimentary basin within the Salgado River watershed contains a system of aquifers created by alternating sandstone and mudstone formations (Fig. 1), enclosed by the crystalline basement (Ponte and Ponte-Filho 1996; Golder-Pivot 2005; Morais Neto et al. 2006). There are three aquifer systems separated by aquitards, which cover 37% of the watershed area; a crystalline basement covers the remaining area. The focus of this study is the Medium Aquifer system (Fig. 1), because it is the main groundwater resource of the Araripe basin with estimated permanent reserves of 21.024×10^9 m^3 and annual average recharge of 27.7×10^6 m^3 (or 12.8 mm) in 2008 and 2009 (Governo do Estado do Ceará 2009).

Recharge of the Superior Aquifer system occurs through direct infiltration of rainfall. The natural discharge of this aquifer occurs at springs emerging at contact with the underlying Santana aquitard on the plateau slope. The Santana aquitard is a very low-permeability formation composed of clayey materials with an estimated hydraulic conductivity of 8.6×10^{-6} m/day (Mendonça 2001). Machado et al. (2007) estimated that about 20% of recharge percolates through the fractures of the Santana aquitard to the Medium Aquifer system.

The Medium Aquifer system is composed of the Rio da Batateira, Abaiara and Missão Velha formations. Mendonça (2001) estimated that the three formations show similar hydrogeological behavior with an average hydraulic conductivity of 4.3 m/day, a total thickness of about 500 m, a specific storage of 10^{-7} m^{-1} and an isotropic flow. The recharge to this system is the sum of direct infiltration of rainfall, channel transmission losses from rivers, and percolation through the Santana aquitard. Artificial discharge occurs through abstraction from numerous boreholes in the area. It is expected that channel transmission losses are

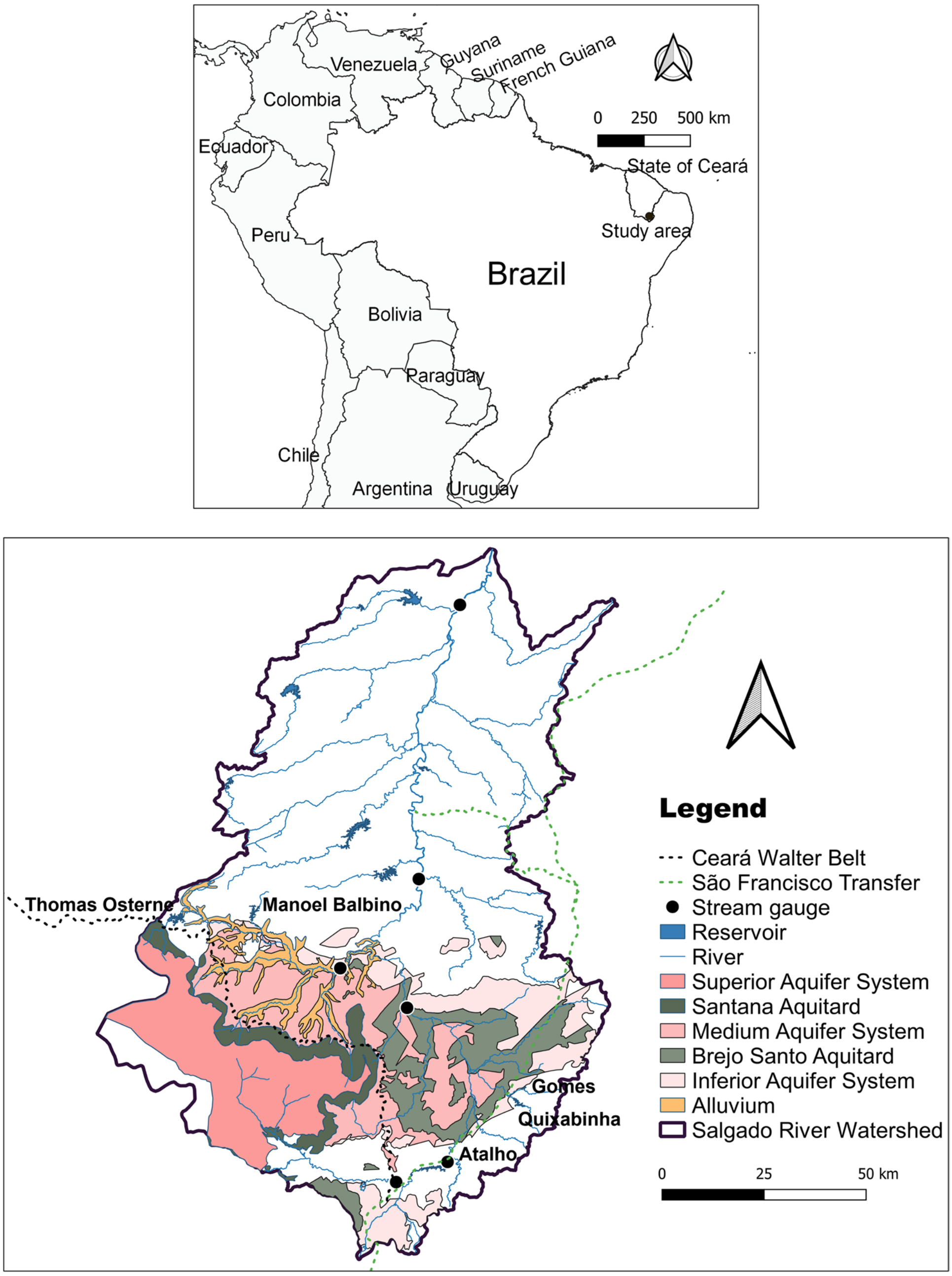


Fig. 1 Location of the Salgado River Watershed in the state of Ceará, Brazil, highlighting the surface-water resources and outcrops of the main hydrogeological units

much larger than groundwater discharge into the rivers due to aquifer overexploitation (Governo do Estado do Ceará 2011; Souza and Costa 2014). The Brejo Santo aquitard is a low permeability formation mostly composed of fine and clayey materials, which separates the Medium Aquifer from the largely confined Inferior Aquifer.

Fifteen strategic surface-water reservoirs, managed by COGERH, are located in the Salgado watershed. However, none is located directly within the Araripe basin because of the high permeability of the sedimentary formations. Nonetheless, part of the surface-water flow into the Araripe basin is regulated by several strategic reservoirs, namely Atalho, Quixabinha, Gomes, Manoel Balbino and Thomas Osterne (Fig. 1).

In the state of Ceará, the SFR water transfer scheme was extended with Ceará's Water Belt project (Cinturão das Águas do Ceará or CAC), consisting of gravity channels to supply water to 12 hydrographic regions (SRH 2022). The first part, Jatí Reservoir – Cariús River (Fig. 1), has a total length of 145.3 km in the Araripe sedimentary basin, with a design discharge of 30 m^3/s. As of early 2022, its construction is close to completion, but its influence on the groundwater resources in the Salgado watershed has not yet been studied.

Materials and methods

Groundwater models, such as MODFLOW (Modular Three-Dimensional Finite-Difference Groundwater Flow Model; McDonald and Harbaugh 1984), can be useful to assess scenarios of surface-water and groundwater management. For instance, aquifer recharge by channel transmission losses occurring at streambeds and banks can be represented in MODFLOW using a built-in model package that calculates the exchange flux between streams and groundwater. Three studies have already applied MODFLOW to quantify the groundwater resources in the Araripe sedimentary basin. They showed, however, poor performance in reproducing the observed groundwater levels, with up to 40 m difference between simulated and observed groundwater head (Golder-Pivot 2005; Rede Cooperativa de Pesquisa 2007; the World Bank 2011).

One reason for that poor model performance may be the oversimplification of the groundwater recharge process. Those studies assumed a constant groundwater recharge rate from the infiltrated rainfall, which neglects both the rainfall temporal variability and the heterogeneity of the soil and land cover. Thus, it could be argued that the choice of using constant recharge rates results in an incomplete representation of groundwater recharge.

Therefore, to model the regional groundwater flow system in the Salgado watershed, the temporal and spatial variation of the infiltrated rainfall within the watershed landscape were included. This process is modelled by WASA (model for water availability in semi-arid environments), which is a semidistributed rainfall-runoff model that has previously been successfully applied in Ceará (e.g., Güntner and Bronstert 2004; Malveira et al. 2012; Mamede et al. 2018). Thus, the use of WASA to simulate the infiltrated rainfall should improve MODFLOW performance in simulating the groundwater resources in the Salgado watershed.

The general approach was first to calibrate WASA using observations from streamflow gauges to estimate groundwater recharge. The results from WASA were used as input for the MODFLOW simulations, which were then calibrated using head time series from monitoring wells. Finally, the integrated modelling, including its uncertainties, was used to assess the potential of the SFR water transfer project to recharge groundwater by channel transmission losses in the Salgado watershed.

The strategy of WASA parameterization and calibration is provided in the electronic supplementary material (ESM). In this section, the focus was on the description of the MODFLOW parameterization, the integration of surface-water and groundwater approaches, and the potential of the SFR transfer for the recharge of the Medium Aquifer, considering the uncertainties involved in the integrated modelling.

Groundwater model parameterization

There are several source codes available to model groundwater flow, such as FEFLOW (Diersch 2014), OpenGeoSys (Kolditz et al. 2012) or AquiMod (Mackay et al. 2014). For this study, the choice of MODFLOW-2005 was made because of its capability to simulate all considered subsurface flow processes, and to be consistent with existing studies in the area thus facilitating comparison with these studies. The Groundwater Modelling System (GMS) software package was used to set up MODFLOW.

The model domain was designed to represent the Medium Aquifer system. Its spatial discretization, a rectangular structured grid, which was required to apply the MODFLOW Control Finite Volume Differences formulation, was selected to simulate the regional groundwater flow. Thus, a fixed grid size of 500 × 500 m was set. The resulting three-dimensional (3D) grid (XYZ) had 208 cells in the X direction, 159 cells in the Y direction and 3 vertical layers, which was based on the main hydrogeological formations in the Medium Aquifer system (Fig. 2).

The area of 2,166 km^2, in which the Medium Aquifer is unconfined, was used to define the flow domain. The cells inside this polygon were active for the calculation of groundwater head, while the cells outside this area were inactivated. This resulted in 26,277 active cells in the grid. The aquifer depth was set to a mean value of 500 m, based on Mendonça (2001). Previous studies assumed homogeneous hydrogeological properties throughout the aquifer. However, in this study, the total depth was divided into three layers of 100, 100 and 300 m from surface to bottom to account for a possible decrease of hydraulic conductivity caused by sediment compaction (based on Medonça 2001). The digital elevation model (DEM) was obtained from Shuttle Radar Topography Mission (SRTM) data with a resolution of 30 m (Farr et al. 2007). Its reliability was confirmed by Governo do Estado do Ceará (2009), who performed a validation of the DEM topography using elevation points collected by a differential global positioning system (DGPS), which reported a good correspondence between satellite and field data.

The lateral boundaries of the Medium Aquifer were characterized by the Santana aquitard in the east, the Brejo Santo aquitard in the west and the crystalline basement at the northern and southern sides (see Fig. 1). Based on these properties, the lateral boundary conditions were set as no-flow boundaries; however, the Superior Aquifer interacts with the Medium Aquifer system by percolation through the Santana aquitard and infiltration of water emerging from springs at the plateau slope at the contact of the Arajara and Santana formations (see the schematic cross section in Fig. 3). This interaction was represented in the model by the MODFLOW Recharge (RCH) package.

The contribution of natural springs located at the cliff of the Araripe plateau to the recharge of the Medium Aquifer

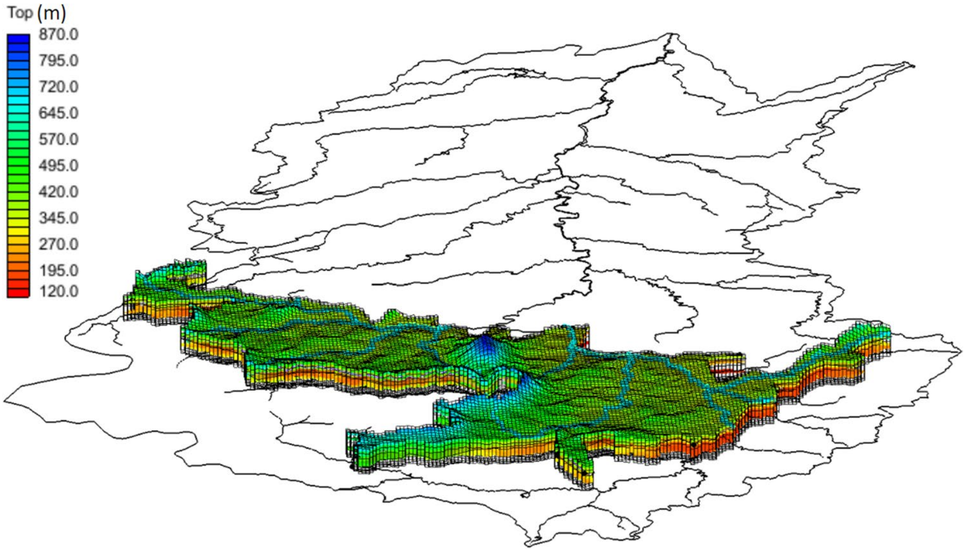


Fig. 2 Oblique view of the MODFLOW 3D grid of the model domain within the Salgado watershed (black contour); streams (black lines and blue lines within the model domain); the spatial discretization in the XY direction is visible as cells at the surface of the domain and in the Z direction as three layers of cells; the elevation is imported to the model surface from a SRTM raster file

was estimated using a database from COGERH and the National Department of Mineral Production (DNPM). The database lists 320 natural springs with data of annual water production and annual authorized water withdrawal.

Information on pumping wells was retrieved from the database of the Brazilian Geological Survey (CPRM), called SIAGAS (CPRM 2020). Wells with no data concerning depth or pumping rate were excluded. In total, 532 wells were registered within the model domain (Fig. 4), which were implemented in the model by the MODFLOW Well (WEL) package, using elevation, depth and pumping rate (m^3/day). Because screen depths were not available for these wells, either a default screen of 10 m was chosen or the wells were assigned automatically to the first layer only (first 100 m) without using screens.

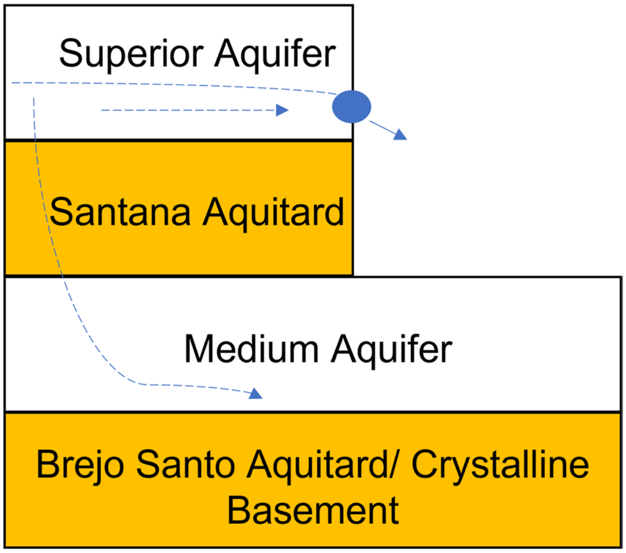


Fig. 3 A schematic cross section of the interaction between the Superior Aquifer and the Medium Aquifer

The SIAGAS database also provided information about the type of groundwater use (public, domestic, irrigation, leisure or multiple uses), as well as the allowed hourly pumping rate. The daily pumping rate implemented in MODFLOW was based on Golder-Pivot (2005), Rede Cooperativa de Pesquisa (2007) and the World Bank (2011). For each well with a pumping rate less than or equal to 50 m^3/h, a daily pumping regime of 8 h was assumed, corresponding to private wells for domestic water use. For wells with a pumping rate greater than 50 m^3/h, a daily pumping regime of 20 h was assumed, corresponding to public and irrigation wells, likely to be pumping water more intensively. The sum of these 532 pumping rates was the artificial discharge of the Medium Aquifer. Assuming that the yearly water demand remained constant during the MODFLOW simulation period (2010–2016), the wells represented an abstraction capacity of 7.14×10^7 m^3/year of water.

Streams were added to the groundwater model using the MODFLOW Streamflow Routing (SFR2) package. The simplified Manning equation was adopted, which required values of the hydraulic conductivity of the streambed, width, sinuosity, roughness and value of incoming flow for each stream segment. The package automatically computes flow between the stream and the aquifer, including the channel transmission losses. Values for the hydraulic conductivity of the streambed and stream geometry for each segment were retrieved from field data (FUNCEME 2018). For stream reaches where no field data were available, the values were inferred from the closest measured stream. The reservoir water released as upstream input discharge was considered for some stream reaches.

The recharge to the Medium Aquifer comprises the infiltrated rainfall generated by the surface-water model WASA.

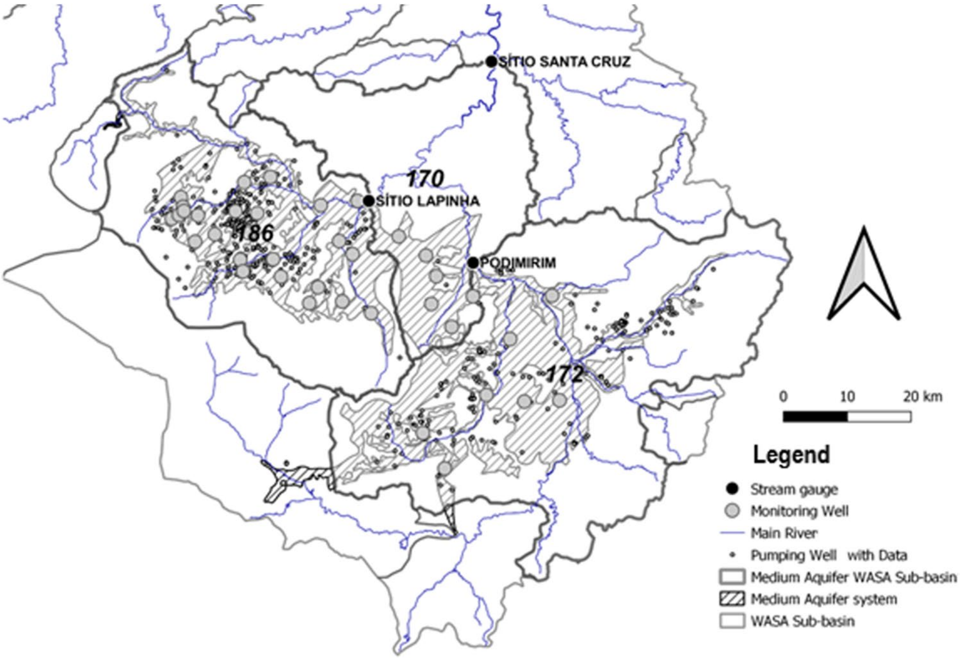


Fig. 4 Location of pumping wells with data and monitoring wells used for MODFLOW calibration in the Salgado River watershed. Also shows WASA subbasins that intersect the Medium Aquifer system and stream gauges used for WASA calibration

Recharge was implemented in the groundwater model MODFLOW as a recharge rate, which was applied to the most upper active cell. The interaction with the Superior Aquifer was also represented using the RCH package at the western boundary of the model as aforementioned. The estimated contribution from the Superior Aquifer using RCH was added to the recharge calculated by WASA. Machado et al. (2007) estimated that 4% of mean annual rainfall infiltrates into the Superior Aquifer System in forested areas, and only one-fifth of this value in the case of deforested areas. They also estimated that about 20% of the total recharge percolates through the Santana aquitard and effectively contributes to the recharge of the Medium Aquifer.

Integrated surface-water and groundwater modelling

WASA was integrated with MODFLOW, using recharge that was generated by WASA as an input variable for MODFLOW. For each subbasin, WASA yielded a monthly time series of the mean daily recharge to groundwater, which was obtained after streamflow calibration (for more details, see ESM). These values were implemented in MODFLOW using the RCH package, by defining polygons following the subbasins contours. Three additional polygons were created at the western boundary, where the estimated contribution from the Superior Aquifer was added to the WASA recharge rates, resulting in six recharge zones (Fig. 5).

Then, MODFLOW simulated the groundwater flow in the Medium Aquifer at a daily scale with a monthly varying recharge rate in each recharge polygon (sufficient to observe seasonal variations). However, the scarcity of field measurements of hydraulic conductivity and storage coefficients added uncertainty to these model parameters. Data for model calibration were the groundwater level time series measured at 26 monitoring wells (Fig. 4) from 2010 to 2016. Calibration using the algorithm PEST (Doherty et al. 1994) allowed

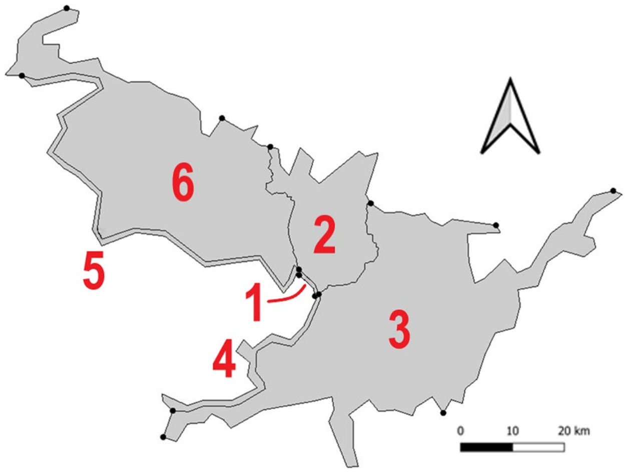


Fig. 5 Recharge zones in the groundwater model. Zone 1: WASA-based recharge from subbasin 170 with contribution of Superior Aquifer. Zone 2: WASA-based recharge from subbasin 170. Zone 3: WASA-based recharge from subbasin 172. Zone 4: WASA-based recharge from subbasin 172 with contribution of the Superior Aquifer. Zone 5: WASA-based recharge from subbasin 186 with contribution of the Superior Aquifer. Zone 6: WASA-based recharge from subbasin 186. The dots represent the limitations of the recharge zones

the determination of the set of parameters that best simulated the observations at monitoring wells.

Potential of the São Francisco River transfer scheme for recharge of the Medium Aquifer

Once the integrated model was calibrated, CAC could be represented in the model as a new channel with the SFR2 package of MODFLOW, releasing water to the main streams in the area. This new input of water to the streams might generate recharge into the Medium Aquifer by channel transmission losses. By carrying out a scenario analysis, i.e. comparing simulations with and without CAC, the effects of this new water management system on the groundwater flow could be assessed. For the scenario analysis, a context of a prolonged drought period was considered, i.e., low groundwater recharge. A scenario analysis approach has been adopted to study the impact of human interventions on surface-water and groundwater resources in other drylands (e.g., Bauer et al. 2006; Izady et al. 2015).

The CAC route was retrieved from a COGERH shapefile and used to create a new SFR2 segment. The channel elevations were estimated from the SRTM raster. The channel width was uniformly set to 20 m, based on design documents. The channel is concreted to preserve the flow of water; thus, the hydraulic conductivity of the streambed was set to 0. The design inflow of 30 m^3/s was set at the entrance of the segment. An evaporation value of 1.5 mm/day was also set to account for the evaporation at the water surface. No data regarding the potential amount of water released from the canal to the subbasin streams were available. Thus, an arbitrary value of 0.29 m^3/s (5,000 m^3/day) was set as inflow to each of the five streams crossed by CAC, in order to preserve the flow to the next canal segments. Since the CAC segment considered here is only a part of this water transfer project (145.3 out of 1,250 km), it was important to ensure that the water release simulation from CAC in the Salgado River watershed does not result in a reduction of flow to the next watersheds crossed by this project.

An uncertainty analysis was also carried out on (1) the simulated groundwater recharge, and (2) the estimation of total pumping volume when CAC was active, since it is not realistic to consider error-free simulated recharge and the pumping rate may be higher during prolonged droughts due to water demand increases, respectively. For the uncertainty analysis on groundwater recharge, it was assumed that the range of recharge uncertainty bounds is proportional to the standard deviation of the error of simulated streamflow, i.e., the observed error at the surface is similar to the error in groundwater recharge. Regarding total pumping volume, an increase of 25 and 50% of the estimated total pumping volume was considered.

Moreover, considering that there is no unique calibration solution for a real-world groundwater modelling application, a MODFLOW parameter sensitivity analysis was carried out to assess the effects of parameter uncertainties on head simulation. Hydraulic conductivity, specific yield and specific storage were selected for the sensitivity analysis, these being the most influential parameters. Then MODFLOW was run, changing individually the selected parameters by the following multiplication factors: 0.1, 0.25, 0.5, 0.75, 1.25, 1.5, 1.75, and 2.0. Finally, the different outputs were plotted and compared.

Results and discussion

WASA calibration

Calibration-free WASA simulation presented monthly river flow higher than the stream gauge observations. Gradual increase of soil-saturated hydraulic conductivity and porosity increased the amount of water infiltrating the soil profile, therefore decreasing runoff. The optimal fit was obtained after increasing the saturated hydraulic conductivity and porosity by 65%.

Figure 6 shows the interannual variability of the monthly discharge. One distinctive period from 2003 to 2009 was characterized by higher peak discharge during the wet season (January to May). On the other hand, a much drier period could be identified from 2010 until 2016, which was characterized by low peak discharge during the wet season. These two periods can be explained by the interannual variability of precipitation, with the presence of a prolonged meteorological drought in the latter period (not shown).

The simulated river discharge time series (Fig. 6) resulted from the calibration with the highest Nash-Sutcliffe efficiency (NSE). Because of the availability of the measured discharge time series, the chosen calibration period for subbasins 186 and 172 was 1995–2016, and for subbasin 170 this was 2000–2016. Non-calibrated simulations from Güntner (2002) resulted in a NSE of –0.54 for subbasin 186, which was improved to 0.73 after calibration, and a NSE of 0.34 for the subbasin 172, which was improved to 0.61.

However, the performance for subbasin 170 did not improve after calibration, with a NSE of 0.70 without calibration and 0.19 with calibration. This can be explained by the fact that most of this subbasin area (Fig. 4) is located in the crystalline domain, i.e., outside the Araripe sedimentary basin, which corresponds more closely to the parameterization in the non-calibrated version of WASA. As a result, the recharge to groundwater that is input to MODFLOW might be an overestimation in the case of subbasin 170. However, this subbasin forms only a small proportion of the total area, which still leads to a low value of groundwater recharge when compared to the recharge calculated from the other subbasins.

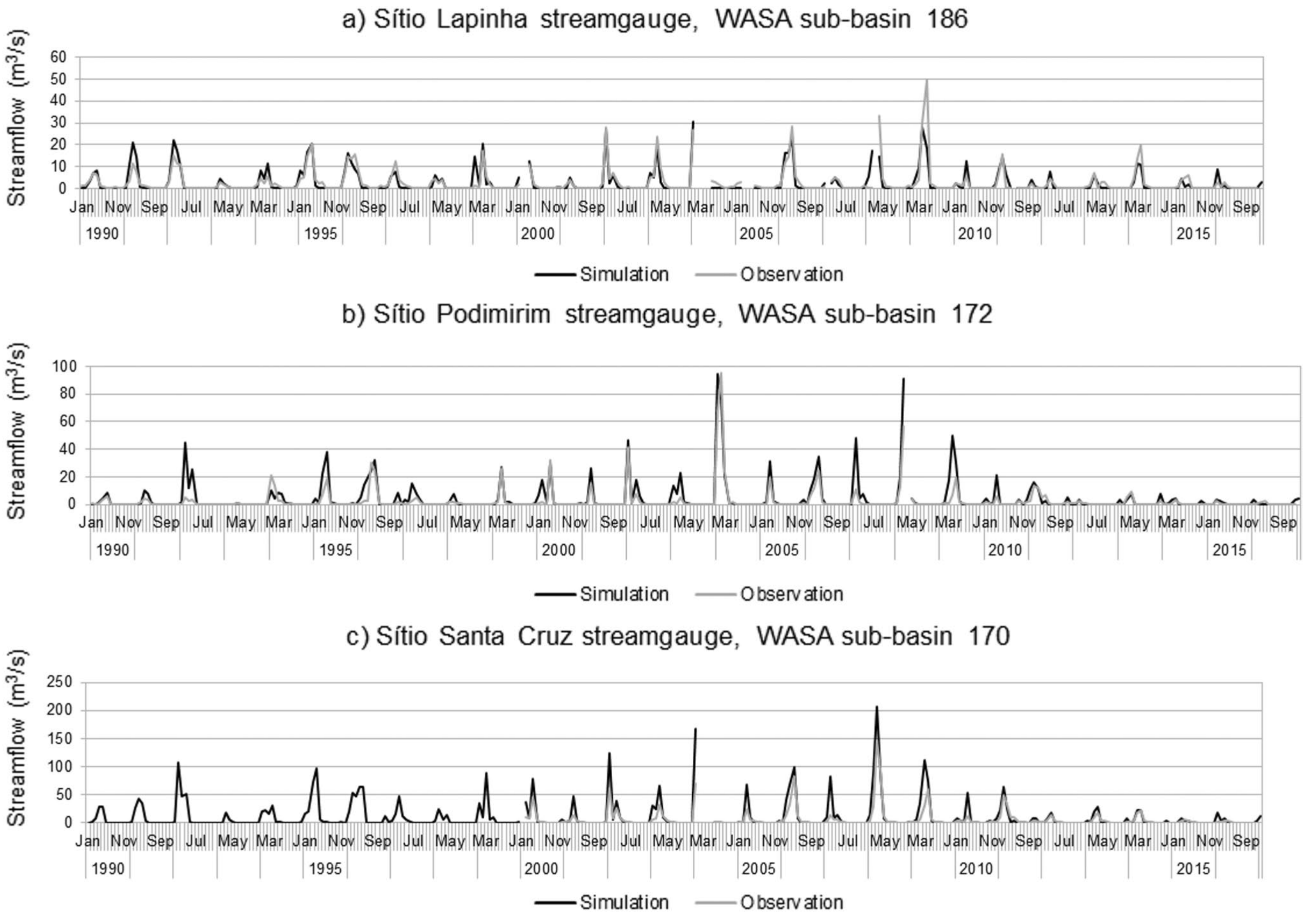


Fig. 6 Observed vs simulated streamflow discharge (m^3/s) after WASA model calibration. **a** Sítio Lapinha streamgauge, WASA subbasin 186; **b** Sítio Podimirim streamgauge, WASA subbasin 172; **c** Sítio Santa Cruz streamgauge, WASA subbasin 170

WASA recharge simulation

WASA provides a separate output file giving daily deep groundwater recharge for each subbasin in meters cubed. These values were converted to millimeters by dividing them by the subbasin area to match the input requirements of the MODFLOW RCH package. As expected from the precipitation and river flow time series, high interannual variability of groundwater recharge was observed, with a maximum annual recharge of 267 mm simulated for subbasin 186 in 2004 and a minimum annual recharge of less than 1 mm simulated in subbasin 172 in 1993, 2012, 2015 and 2016 (Fig. 7).

When comparing the values used in previous studies with the mean annual recharge of each subbasin for the whole calibration period, the recharge rates of 148.2 and 196 mm/year estimated in the Golder-Pivot (2005) and Rede Cooperativa de Pesquisa (2007) studies, respectively, are much higher than the results obtained by WASA (186: 86.8 mm/year; 172: 40.2 mm/year; and 170: 47.6 mm/year), probably because the former studies assumed a very high constant groundwater recharge rate from the infiltrated rainfall. The long-term recharge values from WASA are more similar to those calculated by the World Bank (2011): 60 mm/year in the western part of the aquifer and 16 m/year in the eastern part. Moreover, the latter study showed higher values of recharge in the western part of the Medium Aquifer, which corresponds to the subbasin 186.

Water balance of the subbasins

In order to ensure the reliability of the WASA calibration results, it was assessed whether the contribution of each dominant process to the catchment water balance made hydrological sense in the context of the study area (e.g., semiarid climate, sandy soils and intense rainy seasons). To do so, the proportional values of the WASA outputs were summarized: actual evapotranspiration, surface runoff and recharge regarding rainfall in each subbasin for the whole period of simulation (Fig. 8).

Evapotranspiration was 75–85% of rainfall. The remaining part of rainfall was then distributed over the system

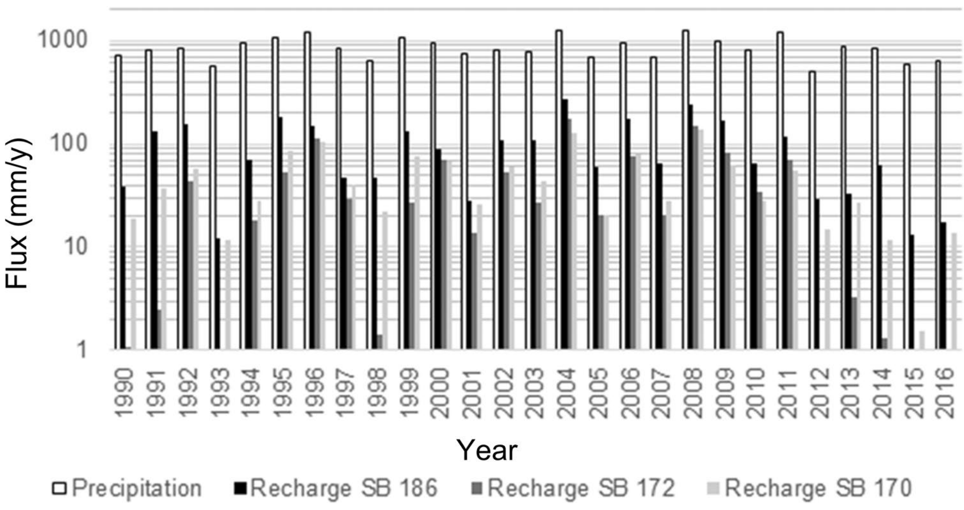


Fig. 7 Simulated annual groundwater recharge (mm) for each WASA subbasin (recharge subbasin (SB) 186, 172 and 170) and annual precipitation over the subbasins

mainly in surface runoff contributing to river discharge (5–18%) and in recharge to groundwater (5–10%). These values of actual evapotranspiration, surface runoff and recharge are typical for semiarid regions like northeast Brazil (Ponce 1995). Other processes involved in the surface-water balance were, e.g., subsurface runoff, storage contents of the soil layer and interception by plants, representing altogether less than 4% of the total contribution.

Although the overall water balance was similar for the three subbasins, some differences in the relative contribution of each process could be related to the input rainfall data combined with the characteristics of the study area. For instance, the higher proportion of surface runoff in subbasins 186 and 170 compared to that from 172 could be explained by higher precipitation in the former. Based on the mean annual precipitation in the three subbasins (subbasin 186: 975 mm; subbasin 172: 737 mm; and subbasin 170: 869 mm), differences in runoff responses are expected. This explained partly the lower contribution of surface runoff to the water balance in subbasin 172, although this subbasin is mainly located over a crystalline basement. This lower surface runoff was compensated by a higher actual evapotranspiration rate.

Water balance of the groundwater system

The order of magnitude of most of the inflows and outflows of the groundwater system could be quantified before MODFLOW application. Here the overall water balance of the Medium Aquifer was presented for the whole period of WASA simulation (1990–2016), based on WASA outputs, available regional data and previous studies (Table 1).

The amount of water percolating through the Santana aquitard to the Medium Aquifer was estimated using the average rainfall time series over the Araripe plateau. For the period 1990–2016, this resulted in a mean annual percolation of 6.5 mm in forested areas and 1.3 mm in deforested areas. When applied to an area of 600 km^2, corresponding to the overlying Santana Formation, the estimated inflow to the Medium Aquifer (2,166 km^2) was 2.3 × 10^6 m^3/year or 1.1 mm/year. The potential amount of water available from the springs located at the cliff of the Araripe plateau was estimated by calculating the difference between water production and withdrawal. The contribution of these springs to recharge was only 6 × 10^5 m^3/year or 0.3 mm/year, considering a 7% infiltration rate, which was based on the recharge rates obtained with WASA. The sum of the contribution

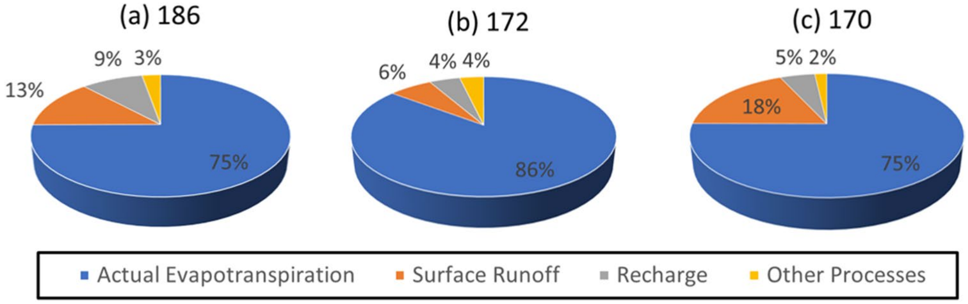


Fig. 8 Mean water balance in the subbasins **a** 186, **b** 172 and **c** 170 for the whole period of simulation. ‘Other processes’ involved in the surface-water balance are, e.g., subsurface runoff, storage content of the soil layer and interception by plants

Table 1 Water balance components of the Medium Aquifer system for the period of 1990–2016, including the catchment rainfall infiltration simulated by WASA model

Component	Value (mm/year)
Catchment rainfall infiltration	64.6
Superior Aquifer percolation[a]	1.4
(Santana aquitard percolation)	1.1
(Recharge from springs)	0.3
Groundwater abstraction	33

[a] Sum of Santana aquitard percolation and recharge from springs

of the Santana aquitard percolation and the recharge from springs is equal to 1.4 mm/year, which is the total contribution of the Superior Aquifer percolation.

Therefore, the total contribution of the Superior Aquifer percolation could be considered negligible in comparison to the catchment rainfall infiltration. The catchment rainfall infiltration was the most relevant component of the Medium Aquifer recharge, being circa 47 times the Superior Aquifer percolation on average. The annual recharge was approximately twice the amount of water abstracted, which indicates an average increase in the water level between 1990 and 2016. This abstraction rate would indicate a sustainable use of groundwater. However, the results from WASA showed a high interannual variability of groundwater recharge. While periods with high rainfall resulted in recharge reaching 184.7 mm/year like in 2008, annual rainfall was much lower from 2012 to 2016, resulting in a mean annual recharge dropping to 13.9 mm. Therefore, when considering this drought period, groundwater abstraction becomes unsustainable, as abstraction is now circa twice the amount of recharge.

In fact, groundwater abstraction might be much higher and, consequently, significantly unsustainable. The study of Golder-Pivot (2005) estimated an annual increase in water demand of 1.77%, which would represent an increase of the abstraction capacity by 1.3×10^6 m^3/year. Moreover, it is expected that during a prolonged drought period, water demand increases, resulting in increased groundwater abstraction.

MODFLOW steady-state simulation

First simulations were run in steady state to reproduce the initial head distribution in the study area, i.e., a stationary situation with no storage change. The abstraction wells were not included to simulate groundwater flow in which inflow was equal to outflow over one hydrological year. The steady-state model using PEST was calibrated to reproduce the initial head distribution observed at monitoring wells on August 1, 2012. The calibration of hydraulic conductivity, recharge rate and hydraulic conductivity of the streambed resulted in the head distribution presented in Fig. 9.

The groundwater flow in the Medium Aquifer after the steady-state calibration showed a general flow direction from S–SW to N–NE. The flow direction was mainly driven by topography, following the downhill slope from the Araripe plateau and converging to the main river network, which are the natural outlets of the aquifer. Channel transmission losses occurred mainly in upstream areas.

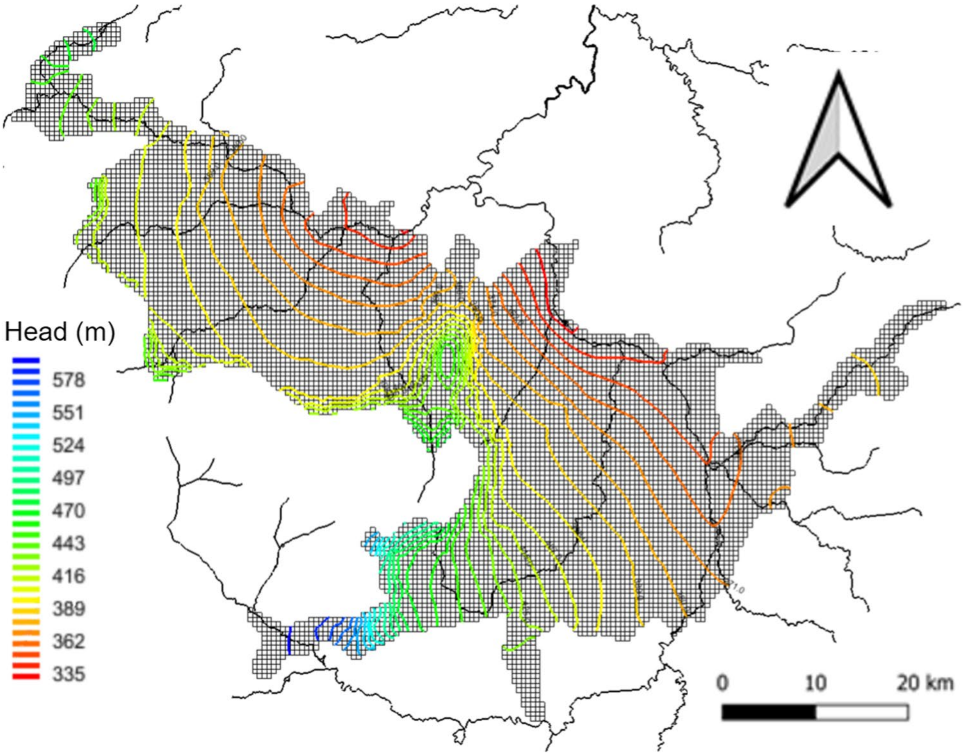
The model's capability to reproduce the head distribution observed could be analysed from the model residuals. The calibration resulted in a mean residual head of –0.62 m, a root mean squared (RMS) residual head of 9.48 m, and a scaled RMS error of 0.23, which is calculated as RMS divided by the range of observed head (i.e., maximum head – minimum head). The largest residual heads were observed in the central part of the model, with a maximum residual of almost 26 m. The lowest residual heads were mainly observed in the western part of the model, with a minimum residual of –18.2 m observed. The coefficient of correlation of 0.925 between observed and simulated head reflects a satisfactory representation of the groundwater flow at the beginning of the transient simulation (Fig. 10).

The values of the parameters obtained after the steady-state calibration (Table 2) were quite different from the initial values set for the Medium Aquifer from previous studies. For instance, the calibrated hydraulic conductivity for layers 2 and 3 (0.1 m/day) seemed to be very low to represent sandy sedimentary formations, which were estimated at about 5 m/day by Mendonça (2001) using pumping test data. In addition, the calibrated recharge was quite different between the recharge zones, whereas the results from WASA were more homogeneous between the subbasins. In fact, it seems unrealistic to observe such drastic spatial changes in recharge rates, which could be explained by a high contribution of groundwater flow to storage in the initial head distribution. Moreover, since recharge is temporally highly variable due to high precipitation variability, it was inappropriate to use the calibrated recharge from the steady-state model for the 4–5 years of transient simulation. Therefore, WASA recharge was used as direct recharge input in the transient model (see next section); however, besides the uncertainties involved, the low mean residual head obtained after steady-state calibration meant this simulation provided satisfactory initial head conditions for the transient calibration of the regional groundwater flow.

MODFLOW integrated with WASA: transient calibration

Simulation of the groundwater flow in transient mode requires imposing stresses on the system varying with time. Here, the recharge was applied as a monthly varying stress

Fig. 9 Head distribution simulation using the MODFLOW model after the steady-state calibration



entering the system to account for the intra-annual variability caused by distinct seasonality and the interannual variability caused by the highly variable annual precipitation. Groundwater flow was then simulated using a monthly time step from September 2012 to September 2016. As stated earlier, the dataset resulting from the steady-state calibration in September 2011 was exported and used as the initial heads for the transient simulation of the groundwater flow in the Medium Aquifer system.

The main issue was compensating for the error introduced by the initial discrepancy in storage, which led to an enormous amount of water leaving the aquifer at the streams in the lowest elevation part of the model domain (NE part, downstream end of the main river network), where the groundwater level was simulated as being several meters above the streambed elevation. Ultimately, a transient calibration of the model was performed, adjusting the hydraulic conductivities of the three layers, the hydraulic conductivity of the streambed, and the specific yield. The model calibration showed satisfactory results with a mean residual head of –1.15 m and an RMS residual head of 10.27 m for the total simulation period, with optimal parameters presented in Table 3.

Figure 11 shows the changes of hydraulic head over the simulation period. No large change of regional flow

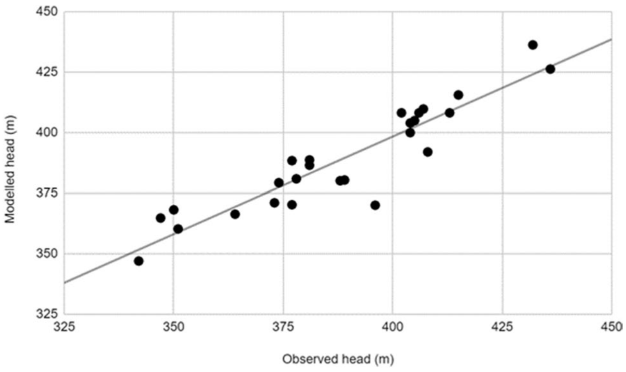


Fig. 10 Observed vs modelled heads (m) in steady-state calibration

Table 2 MODFLOW calibration parameters for the steady-state simulation

Parameter	Optimal value (m/day)	Optimal value (mm/year)
Hydraulic conductivity: layer 1	11.8	-
Hydraulic conductivity: layer 2	0.1	-
Hydraulic conductivity: layer 3	0.1	-
Hydraulic conductivity of the streambed	5.0	-
Recharge rate: zone 1	-	1.4
Recharge rate: zone 2	-	188.7
Recharge rate: zone 3	-	31.1
Recharge rate: zone 4	-	152.9
Recharge rate: zone 5	-	365.0
Recharge rate: zone 6	-	18.7

Table 3 Optimal parameters of the transient calibration of the MODFLOW model

Parameter	Optimal value (m/day)
Hydraulic conductivity: layer 1	0.79
Hydraulic conductivity: layer 2	1.03
Hydraulic conductivity: layer 3	3.10
Hydraulic conductivity of the streambed	2.21
Specific yield	0.16

direction or water level could be observed, in accordance with the low recharge computed for the period 2012–2016 (Fig. 7). The main change from Figs. 11a to 11b was a decrease in the groundwater dome presented in the central part of the model domain. This change may be attributed to the overestimation of the groundwater level in the initial head distribution. A steady decrease of the hydraulic head could be observed in the model over the period of simulation in the northwestern part of the model, which could be explained by the high density of pumping wells in this area (Fig. 4).

The capability of the calibrated model to reproduce the intra-annual and interannual variations of the hydraulic head at monitoring wells differed in the study area. The model accurately reproduced the interannual head variations in the northwest (corresponding to WASA subbasin 186) such as shown in Fig. 12a,b; this area comprises 25 boreholes (66% of the total). On the other hand, performance was much poorer in the central part (equivalent to subbasin 170) as shown in Fig. 12c,d, and in the southeast (subbasin 172) as shown in Fig. 12e,f. In these latter two areas, the poorer calibration represents much fewer boreholes; thus, local aquifer heterogeneities are more influential on the discrepancies between simulated and observed heads. This could be partly explained by the performance of WASA in estimating recharge in the three subbasins (see NSE of the calibrated WASA model). WASA performed better at reproducing discharge at the outlet of subbasin 186. The groundwater modelling uncertainties may also be related to the simplified representation of the geology—e.g., no variation of lithology and sediment thickness—and the groundwater abstraction data scarcity.

The comparison between the performance of the WASA-MODFLOW modelling and three previous models

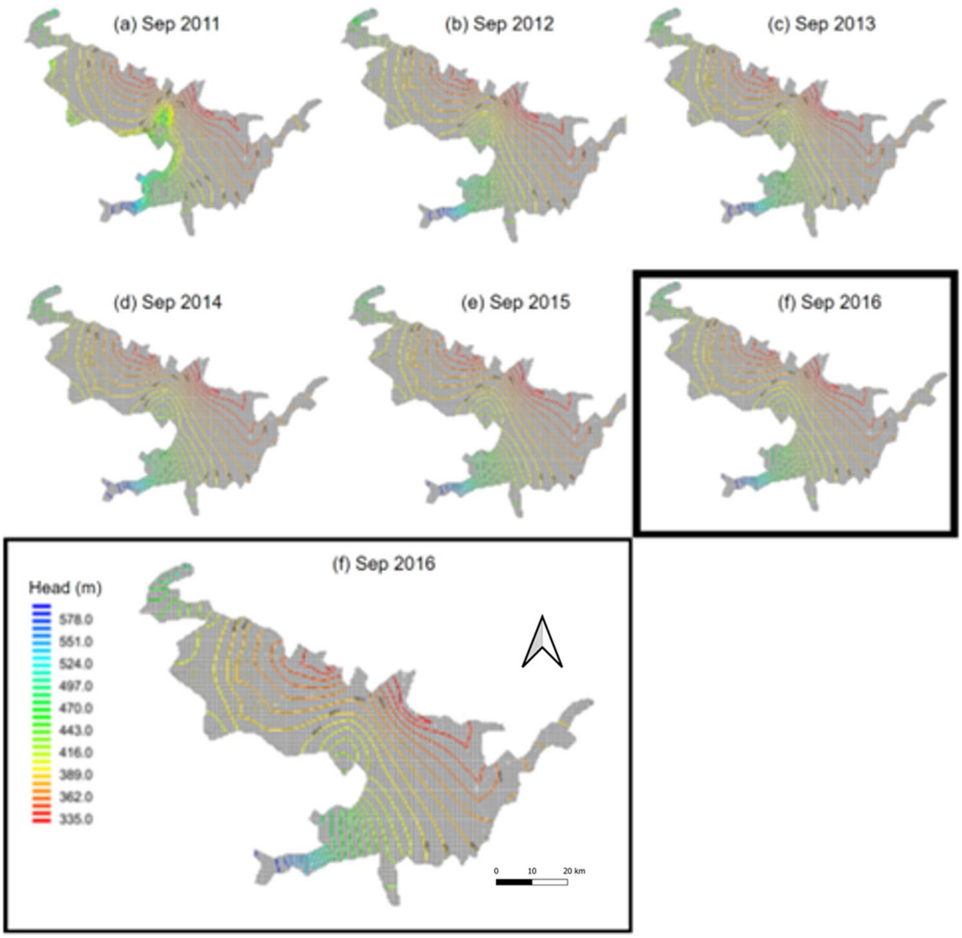


Fig. 11 Evolution of the head distribution (m) for the calibrated transient simulation of the MODFLOW model. **a**–**f** September 2011 to September 2016. The end of simulation (September 2016) is enlarged for a better visualization

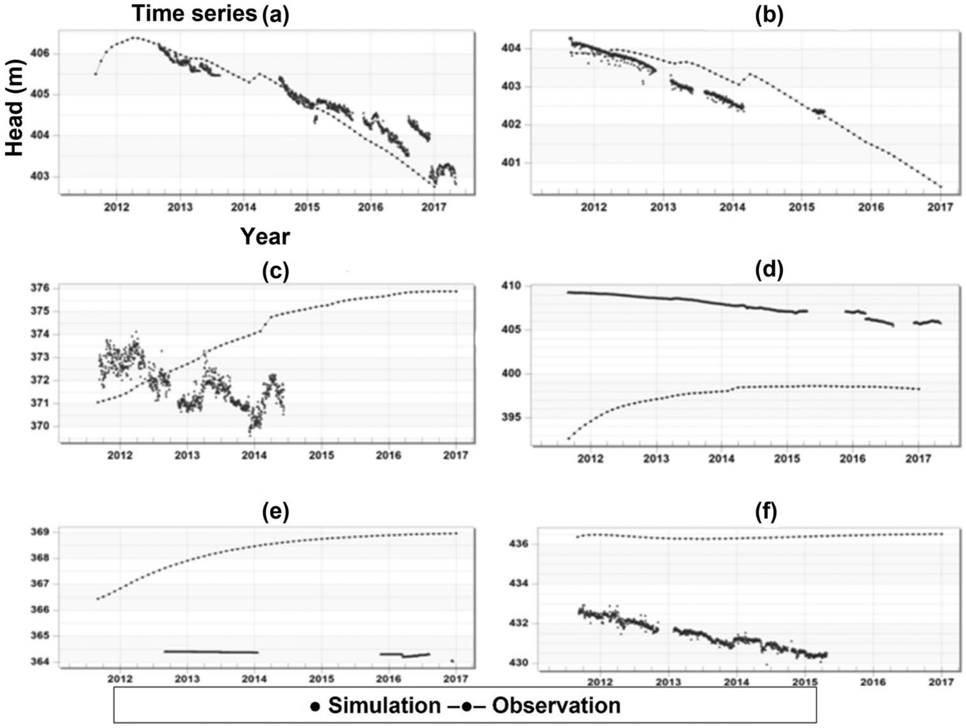


Fig. 12 Plots of simulated and observed head (m) at six monitoring wells: **a**–**b** located in the western part of the model domain where the model reproduces the observations most accurately and represent 66% of monitoring wells; **c**–**d** located in the central part of the domain where the model performance to reproduce observed heads are poor; **e**–**f** located in the east where there is a large discrepancy between model and the heads at the monitoring wells

is summarized in Table 4, which shows that the model performance was an improvement in steady-state simulation compared to the studies of Golder-Pivot (2005) and the World Bank (2011). For transient simulations, the model of this study performed much better than that from Rede Cooperativa de Pesquisa (2007). Also, for transient simulations, the WASA-MODFLOW modelling performance was similar to the model performance in the study of the World Bank; however, this comparison of performances should be considered with caution since the aim of the study, size of modelled area, modelling approach and data used for calibration were quite different between the considered studies.

Simulation of the São Francisco River transfer scheme for recharge of the Medium Aquifer

The Ceará Water Belt was added to the modelling as a new SFR2 segment. For small discharges, such as the CAC releases, it was also assumed that flows were concentrated in streambed paths that have much lower hydraulic conductivity than the total streambed area and river banks (Lange 2005; Souza and Costa 2014). Therefore, assuming the presence of clogging layers with hydraulic properties similar to silty clay soils, this study assessed the hydraulic conductivity of the streambed for the five streams receiving water from CAC equal to 2.21 m/day (calibrated value) and 0.01

Table 4 Summary of model performances of the MODFLOW-WASA and three previous models

Simulation	Residuals (m)	Integrated MODFLOW-WASA	Golder-Pivot (2005)	Rede Cooperativa de Pesquisa (2007)	World Bank (2011)
Steady-state	Mean residual head	–0.62	11.8	-	–2.65
	RMS residual head	9.48	21.15	-	14.13
	Maximum head difference	25.9	40.8	-	–34.9
	Minimum head difference	–18.2	1.1	-	–23
Transient	Mean residual head	–1.15	-	-	–0.51
	RMS residual head	10.27	-	27.88 (CPRM wells); 14.4 (COGERH wells)	9.757
	Maximum head difference	25.9	-	-	29.58
	Minimum head difference	–18.2	-	-	–1.35

m/day (new assumed value), which avoided having all the water released from infiltrating into the aquifer in the first stream cells.

The potential of the SFR water transfer-CAC implementation was investigated by running the calibrated MODFLOW in transient mode for 5 years beyond the end of the head time series, i.e., a scenario from August 2016 to January 2022. The scenario results were compared with and without CAC. The head distribution of the calibrated transient model for August 2016 was set as the initial condition. The recharge time series for the 2011–2016 simulation, which was a period of severe drought, was replicated for the 2016–2022 scenario, to assess the potential of the water transfer scheme in the context of a prolonged drought.

Considering a streambed hydraulic conductivity of 0.01 m/day, the implementation of CAC led to an increase of the hydraulic head by up to 3 m at the outlet of the Medium Aquifer system after 5 years (2016–2022 scenario; Fig. 13). Moreover, there was an average increase of the hydraulic heads over the study area of 0.5–1 m. The daily amount of groundwater recharge by channel transmission losses resulting from water release of CAC was estimated as 1.89×10^4 m^3, which represented an additional recharge of 6.89×10^6 m^3/year in the context of a prolonged drought. However, it is important to note that the CAC-driven recharge input did not compensate for the relevant decrease of the hydraulic heads in areas that do not surround the receiving streams (Fig. 13), resulting from the joint effect of low natural recharge (drought) and high groundwater pumping. Therefore, the water transfer scheme would represent an additional source of recharge to the Medium Aquifer, but it would not solve alone the issue of unsustainable management of groundwater resources, a result also confirmed even when a streambed hydraulic conductivity was 2.21 m/day. The difference from this scenario was only a concentration of higher heads (from 0.25 to 1.50 m) in the upstream parts of the Medium Aquifer (Fig. 14); however, it clearly indicated that water transportation downstream and beyond the Medium Aquifer system may be more difficult due to higher streambed hydraulic conductivity.

Assessing a variation of ±25% of the simulated groundwater recharge in the 2016–2022 scenario, which is proportional to the observed error of WASA-based simulated streamflows, it was found that an increase of 25% in the groundwater recharge presented a low influence on the hydraulic heads with most of the head differences close to

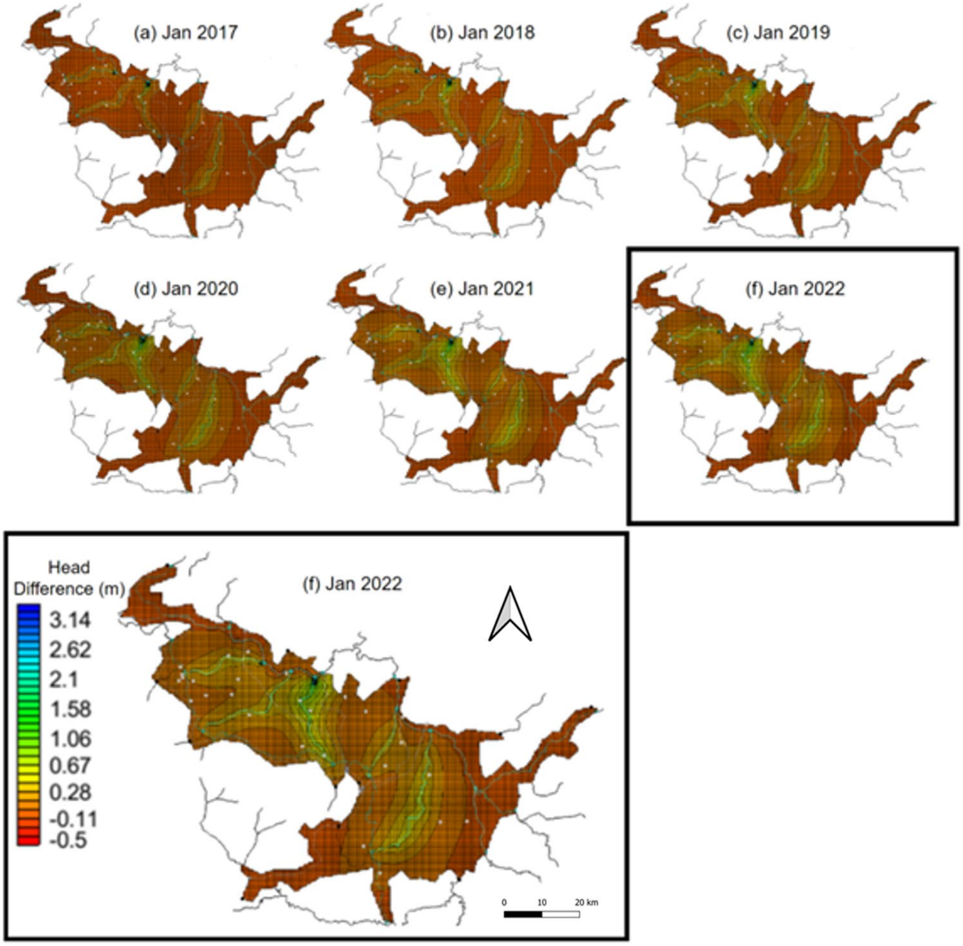


Fig. 13 Evolution of the head difference (m) between the simulation with CAC active and without CAC at different times of simulation, considering a streambed hydraulic conductivity of 0.01 m/day. **a**–**f** January 2017 to January 2022. The end of simulation (January 2022) is enlarged for a better visualization

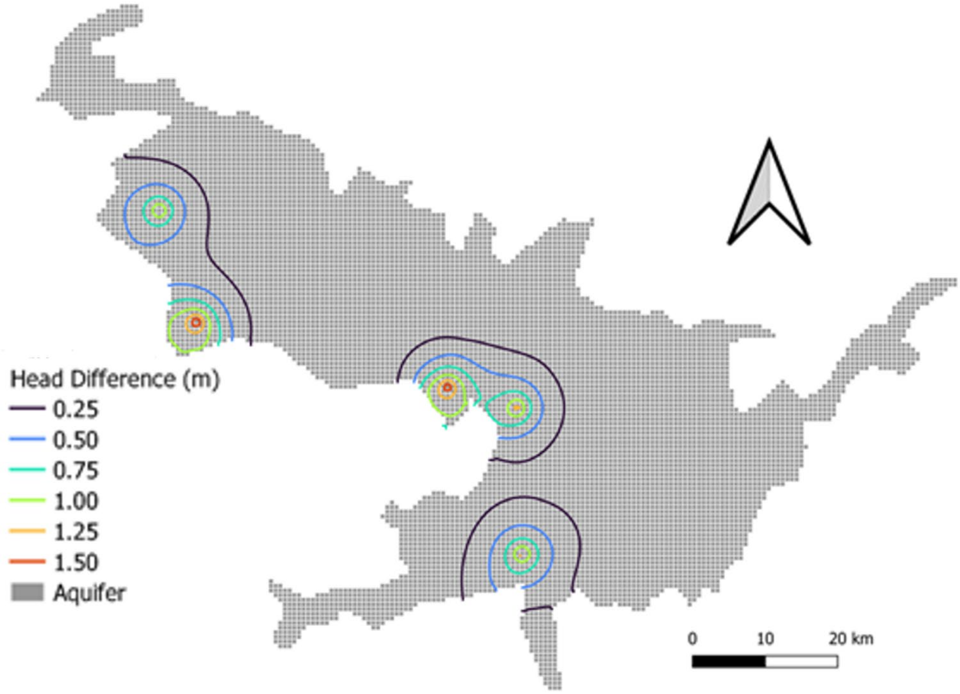


Fig. 14 The head difference (m) between the simulation with CAC active and without CAC at the end of simulation, considering a streambed hydraulic conductivity of 2.21 m/day

zero (Fig. 15a). The head differences are defined as the differences between the changed simulated recharge and the original one. On the other hand, a decrease of 25% in the groundwater recharge was enough to reduce the head difference around –1.0 m (Fig. 15b), which practically balances the gains from the CAC-driven recharge input; therefore, severe droughts may impose even a greater challenge for managed aquifer recharge in the Salgado River watershed.

An increase of 25 and 50% of the estimated total pumping volume was assessed, since water demand increases may trigger higher pumping rates during prolonged droughts. It was found that an increase of 25 and 50% of the estimated total pumping volume has a relevant negative impact on the groundwater level in the northwest, which makes the gains from the CAC-driven recharge input negligible (Fig. 16a). On the other hand, this higher pumping rate scenario showed a low impact on the groundwater level in the southeast (Fig. 16b); therefore, this uncertainty analysis suggested a larger artificial recharge demand in the northwest, and that water transportation downstream and beyond the Medium Aquifer is preferable to using the streams in the southeast.

Finally, evaluating the influence of MODFLOW parameter uncertainties on head simulation (see the outputs of MODFLOW parameter sensitivity analysis in ESM), it was found that lower hydraulic conductivities and lower specific yields presented the largest impacts on head simulation, principally in the northwest and in the central part of the model domain with predominantly lower head (Figs. S1 and S2 in the ESM), while higher hydraulic conductivities and higher specific yields presented negligible influence on head simulation surrounding the receiving streams (Figs. S1 and S2 in the ESM). The changes in specific storage presented very low influence on head simulation in most parts of the modelling domain with a head difference less than 0.5 m. If the order of magnitude of hydraulic conductivities and specific yields were not matched, a larger artificial recharge demand would be necessary to balance the lower groundwater level in the northwest and in the central part of the Medium Aquifer system. On the other hand, this parameter sensitivity analysis confirmed that water transportation downstream and beyond the system is preferable using the streams in the southeast, because of low influence of parameter changes on the region surrounding them.

Research implications for integrated water resources management

When interbasin water transfers are planned, many dimensions must be considered, including engineering, economics, climatology, ecology, law, and politics (Gupta and van der Zaag 2008). Problems and controversies consistently accompany such projects, especially the increasingly common water transfer 'mega-projects' (Shumilova et al. 2018). For example, the world's largest such project, the South-to-North Water Diversion Project in China, has been plagued with controversies since conceptualisation in the 1950s over the involuntary resettlement of 100,000s of people, unequal economic development in donor and recipient basins, and potential downstream water quality impacts and salinisation of agricultural land (Shao et al. 2003; Rogers et al. 2020).

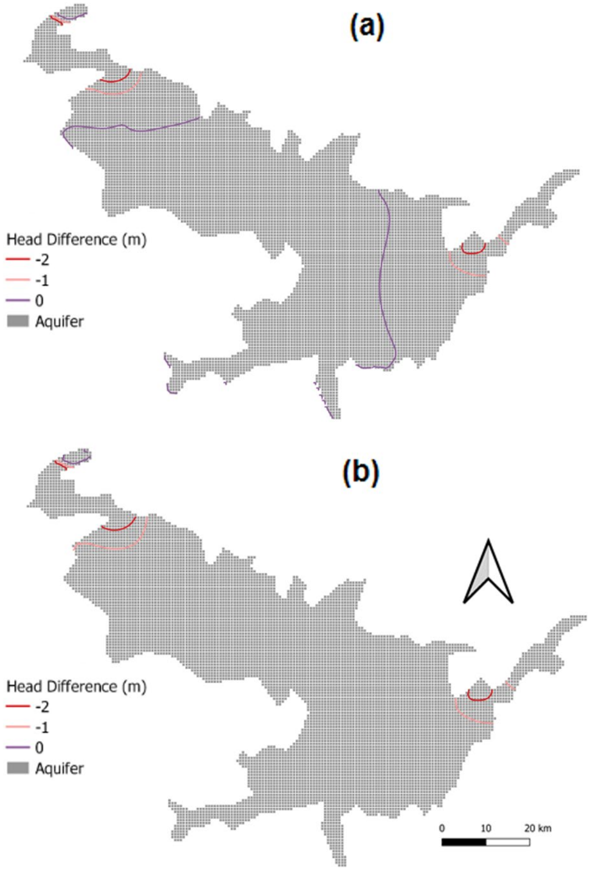


Fig. 15 **a** The head difference (m) between the simulation with +25% groundwater recharge and without groundwater recharge changes at the end of simulation; and **b** the head difference (m) between the simulation with –25% groundwater recharge and without groundwater recharge changes at the end of simulation

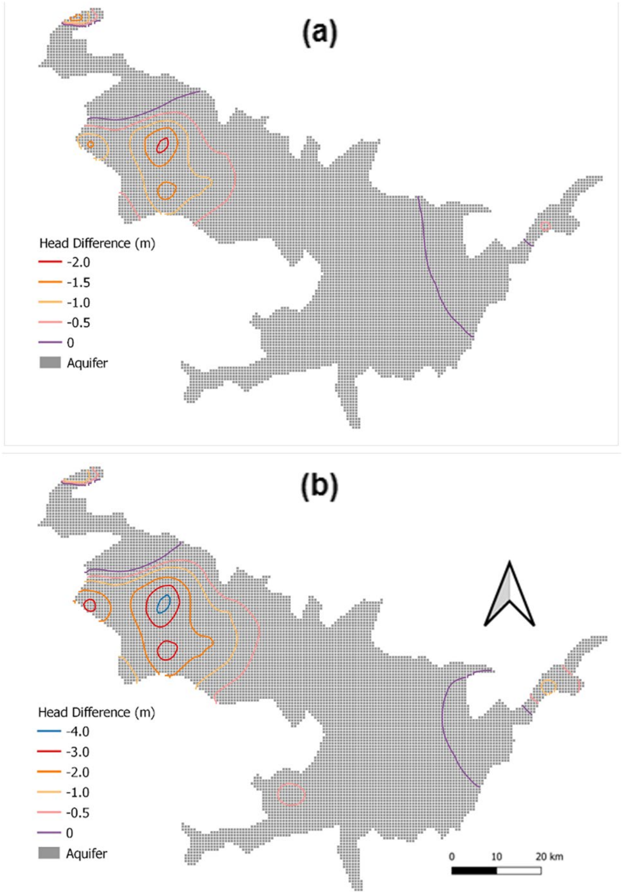


Fig. 16 **a** The head difference (m) between the simulation with +25% pumping rate and without pumping rate changes at the end of simulation; and **b** the head difference (m) between the simulation with +50% pumping rate and without pumping rate changes at the end of simulation (**b**)

While this study does not seek to respond to most of these seemingly inherent controversies, it can counter several reported criticisms of interbasin water transfer schemes and suggest how they can contribute to integrated water resources management (the examples here are from Brazil but are applicable elsewhere). Firstly, conflict has been reported between donor and recipient basins of the Paraíba do Sul River water transfer scheme when drought forced inadequate downstream flows (de Andrade et al. 2011). The findings of this study show that increased groundwater availability, at least in the vicinity of the streams, could buffer periods of drought. Secondly, riparian communities to the São Francisco Transbasin Project have spoken of concerns of water being prioritised for large economic centres (de Andrade et al. 2011). The modelling demonstrated that equivalent communities riparian to the CAC and its receiving streams should benefit from enhanced groundwater recharge augmenting their water resources. Thirdly, while not a criticism of interbasin water transfers per se, Brazil has been criticized for being behind in promoting managed aquifer recharge, a successful solution to water scarcity in other semiarid regions of the world (Shubo et al. 2020). This study demonstrates the viability of artificially recharging aquifers via interbasin transfers, where the hydrogeology allows.

Summary and conclusions

This research investigated the groundwater recharge of the Medium Aquifer system (2,166 km^2) in the state of Ceará, NE Brazil, and the potential influence of the São Francisco River interbasin water transfer scheme on these groundwater resources, using an integrated surface-water/groundwater modelling approach.

The average groundwater recharge was 66 mm/year for the period of 1990–2016 (27 years), which was 7.7% of the average precipitation (860.3 mm/year). The catchment rainfall infiltration represented approximately 97.9% of the total groundwater recharge, while the annual recharge was approximately twice the amount of water abstracted (33 mm/year). This abstraction rate would indicate a sustainable use of groundwater; however, the mean annual recharge dropped to 13.9 mm from 2012–2016. Therefore, when considering this drought period, the groundwater abstraction becomes unsustainable, as abstraction was circa twice the amount of recharge, which drove the observed decrease of groundwater level in the study area. This groundwater level trend was accurately reproduced by MODFLOW in the northwest of the domain, where there is the highest density of pumping wells.

Part of the water transfer system's extension, called the Ceará Water Belt (CAC), was added to the integrated WASA-MODFLOW modelling, using the MODFLOW SFR2 package. After 5 years of scenario simulation, the CAC-driven recharge input due to channel transmission losses led to an increase of the hydraulic head of 0.5–1 m over the study area or 6.89×10^6 m^3/year in a context of a prolonged drought. This result shows that SFR water transfer could decrease the stress on groundwater resources in the Medium Aquifer; however, it is important to note that the CAC-driven recharge input did not compensate for the relevant decrease of the hydraulic heads in areas that do not surround the receiving streams, independently of the scenario assumed, resulting from the joint effect of low natural recharge and high groundwater pumping. Therefore, the water transfer scheme would represent an additional source of recharge to the Medium Aquifer, but it would not solve alone the issue of the unsustainable management of groundwater resources. This conclusion is also supported by the uncertainty analysis, which showed that a decrease of 25% in the natural recharge or an increase of 50% of the pumping rate counteracts the gains from the CAC-driven recharge inputs. However, the uncertainty analysis also showed that water transportation downstream and beyond the Medium Aquifer is preferable using the streams in the southeast.

The CAC implementation in the integrated WASA-MODFLOW modelling yielded encouraging results for the use of the developed modelling as a support tool in decision-making. Moreover, an advantage of the integrated WASA-MODFLOW modelling developed here is that it can be easily modified to investigate future scenarios, beyond the interbasin water transfer—for instance, different scenarios of climate change could be investigated by using projected meteorological time series as input in the calibrated version of WASA. Further scenarios of increase in water demand could also be investigated, including a higher pumping rate in the southeast.

However, the poorer groundwater model performance in the central and southeast parts of the domain may limit reliable conclusions over the whole study area. Although a parameter sensitivity analysis and an uncertainty analysis were carried out, further work should still focus on the reduction of modelling uncertainties. The modelling uncertainties may be related to the large area being modelled, poor representation of hydrological fluxes in the central part of the model domain, the simplified representation of the geology, e.g., no variation of lithology and sediment thickness, and the groundwater abstraction data scarcity. More extensive fieldwork, especially pumping tests and geophysics, and improved groundwater-level and abstraction monitoring would reduce the uncertainties.

The broader implications of the study are in demonstrating that controlled releases of water from interbasin transfers into the river systems where they intersect can quantifiably increase groundwater availability where the hydrogeology is favourable. Whether, like here, this benefit is restricted to areas in close proximity to the receiving streams would require contextualised investigation—for that purpose, the modelling methodology utilised in this study is readily transferable to other water transfer schemes and underlying aquifers.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10040-023-02612-x.

Acknowledgements We thank Dr. Klaas Metselaar (Wageningen University) for his support and collaboration in developing the methodological setup of this study. We also thank the Brazilian National Water Agency (ANA), the Research Institute of Meteorology and Water Resources (FUNCEME), the Water Company of the State of Ceará (COGERH) and the Brazilian Geological Service (CPRM) for streamflow, meteorological, reservoir and groundwater data, respectively.

Funding information This work was supported by the Brazilian National Council for Scientific and Technological Development (Grant No. 404255/2013-2) and the Dutch Research Council (NWO) [project W 07.30318.016]

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose.

References

Bauer P, Gumbricht T, Kinzelbach W (2006) A regional coupled surface water/groundwater model of the Okavango Delta, Botswana. Water Resour Res 42:1–15. https://doi.org/10.1029/2005WR004234

Campos JNB (2015) Paradigms and public policies on drought in Northeast Brazil: a historical perspective. Environ Manage 55:1052–1063. https://doi.org/10.1007/s00267-015-0444-x

Caúla BQ, de Moura GB (2006) Aspectos ambientais e jurídicos da transposição do Rio São Francisco [Environmental and legal aspects of the São Francisco River transposition]. In: III Encontro da ANPPAS, ANPPAS, Brasília

Costa AC, Foerster S, de Araújo JC, Bronstert A (2013) Analysis of channel transmission losses in a dryland river reach in northeastern Brazil using streamflow series, groundwater level series and multitemporal satellite data. Hydrol Process 27:1046–1060. https://doi.org/10.1002/hyp.9243

Costa WD, Neto MS, Souza FJA (1998) Plano de gestão da APA da Chapada do Araripe – CE/PE/PI: estudos dos recursos hídricos [Plan of management of the APA of Chapada do Araripe - CE/PE/PI: water resources studies]. FUNDETEC, Brasília

Costa AC, Bronstert A, de Araújo JC (2012) A channel transmission losses model for different dryland rivers. Hydrol Earth Syst Sci 16:111–1135. https://doi.org/10.5194/hess-16-1111-2012

CPRM (2020) Sistemas de Informações em Águas Subterrâneas – SIAGAS [Brazilian groundwater information system]. CPRM, Rio de Janeiro. http://siagasweb.cprm.gov.br/layout/pesquisa_complexa.php. Accessed 15 January 2020

Davies BR, Thoms M, Meador M (1992) An assessment of the ecological impacts of inter-basin water transfers, and their threats to river basin integrity and conservation. Aquat Conserv 2(4):325–349

de Andrade JGP, Barbosa PSF, Souza LCA, Makino DL (2011) Interbasin water transfers: the Brazilian experience and international case comparisons. Water Resour Manag 25(8):1915–1934

Diersch HJG (2014) FEFLOW finite element modelling of flow, mass and heat transport in porous and fractured media. Springer, Heidelberg, Germany. https://doi.org/10.1007/978-3-642-38739-5_1

Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C (2019) Sixty years of global progress in managed aquifer recharge. Hydrogeol J 27(1):1–30

Doherty J, Brebber L, Whyte P (1994) PEST: model-independent parameter estimation. Watermark, Brisbane, Australia

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D, Alsdorf D (2007) The Shuttle Radar Topography Mission. Rev Geophys 45(RG2004):1–33. https://doi.org/10.1029/2005RG000183

FUNCEME (2018) Sistema de gerenciamento integrado dos recursos hídricos superficiais e subterrâneos da Bacia do Rio Salgado: relatório final [Integrated management system of groundwater and surface water resources of the Salgado River Basin: final report]. Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME), Fortaleza, Brazil

Golder-Pivot (2005) Implantação do sistema de monitoramento/gestão de uma área piloto do aqüífero Missão Velha na bacia sedimentar do Cariri: Caracterização hidrogeológica do sistema sedimentar do graben Crato-Juazeiro no vale do Cariri (CE) [Implementation of a monitoring system/management of a pilot area of Missão Velha aquifer]. Golder-Pivot, Fortaleza, Brazil

Governo do Estado do Ceará (2011) Projeto de gestão integrada dos recursos hídricos do Ceará – PROGERIRH II [Integrated management of water resources of Ceará – PROGERIRH II]. Companhia de Gestão dos Recursos Hídricos, Fortaleza, Brazil

Governo do Estado do Ceará (2009) Plano de monitoramento e gestão dos aquíferos da bacia do Araripe, Estado do Ceará [Monitoring plan and management of aquifers in the Araripe Basin, State of Ceará]. Companhia de Gestão dos Recursos Hídricos, Fortaleza, Brazil

Güntner A (2002) Large-scale hydrological modelling in the semi-arid north-east of Brazil. PhD Thesis, University of Potsdam, Potsdam, Germany

Güntner A, Bronstert A (2004) Representation of landscape variability and lateral redistribution processes for large-scale hydrological modelling in semi-arid areas. J Hydrol 297:136–161. https://doi.org/10.1016/j.jhydrol.2004.04.008

Gupta J, van der Zaag P (2008) Interbasin water transfers and integrated water resources management: where engineering, science and politics interlock. Phys Chem Earth 33(1–2):28–40

Gutiérrez APA, Engle NL, de Nys E, Molejón C, Martins ES (2014) Drought preparedness in Brazil. Weather Clim Extrem 3:95–106. https://doi.org/10.1016/j.wace.2013.12.001

Henkes SL (2014) A política, o direito e o desenvolvimento: um estudo sobre a transposição do Rio São Francisco [Politics, law and development: a study on the transposition of the São Francisco River]. Rev Direito GV 10:497–534. https://doi.org/10.1590/1808-2432201421

Instituto Brasileiro de Geografia e Estatística (IBGE) (2012) Censo Brasileiro de 2010 (Brazilian Census of 2010). IBGE, Rio de Janeiro. https://censo2010.ibge.gov.br/. Accessed 10 January 2020

Izady A, Davary A, Alizadeh A, Ziaei AN, Akhavan S, Alipoor A, Joodavi A, Brusseau ML (2015) Groundwater conceptualization and modeling using distributed SWAT-based recharge for the semi-arid agricultural Neishaboor plain, Iran. Hydrogeol J 23:47–68. https://doi.org/10.1007/s10040-014-1219-9

Kolditz O, Bauer S, Bilke L, Böttcher N, Delfs JO, Fischer T, Görke UJ, Kalbacher T, Kosakowski G, McDermott CI, Park CH, Radu F, Rink K, Shao H, Shao HB, Sun F, Sun YY, Singh AK, Taron J et al (2012) OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. Environ Earth Sci 67:589–599. https://doi.org/10.1007/s12665-012-1546-x

Lange J (2005) Dynamics of transmission losses in a large arid stream channel. J Hydrol 306:112–126. https://doi.org/10.1016/j.jhydrol.2004.09.016

Lima LC (2005) Além das águas, a discussão no nordeste do Rio São Francisco [Beyond the waters, the discussion in the northeast of the São Francisco River]. Rev Depart Geogr USP 17:94–100. https://doi.org/10.7154/RDG.2005.0017.0007

Mackay JD, Jackson CR, Wang L (2014) AquiMod user manual (v1.0). British Geological Survey, Keyworth, UK

Machado CJF, Santiago MMF, Mendonça LAR, Frischkorn H, Mendes Filho J (2007) Hydrogeochemical and flow modeling of aquitard percolation in the Cariri Valley-Northeast Brazil. Aquat Geochem 13:187–196. https://doi.org/10.1007/s10498-007-9015-y

Malveira VTC, de Araújo JC, Güntner A (2012) Hydrological impact of a high-density reservoir network in the semiarid north-eastern Brazil. J Hydrol Eng 17:109–117. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000404

Mamede GL, Güntner A, Medeiros PHA, de Araújo JC, Bronstert A (2018) Modeling the effect of multiple reservoirs on water and sediment dynamics in a semiarid catchment in Brazil. J Hydrol Eng 23:1–13. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001701

Mendonça LAR (2001) Recursos hídricos da Chapada do Araripe [Water resources of the Araripe Plateau]. PhD Thesis, Federal University of Ceará, Fortaleza, Brazil

Mendonça LAR, Frischkorn H, Santiago MMF, Mendes Filho J (2005) Isotope measurements and ground water flow modeling using MODFLOW for understanding environmental changes caused by a well field in semiarid Brazil. Environ Geol 47:1045–1053. https://doi.org/10.1007/s00254-005-1237-y

McDonald MG, Harbaugh AW (1984) A modular three-dimensional finite-difference ground-water flow model. US Geological SurveyReston, VA

Ministério da Integração Nacional (2004) Projeto de Integração do Rio São Francisco com Bacias Hidrográficas do Nordeste Setentrional [Project for the Integration of the São Francisco River with the Northeastern Watersheds]. Ministério da Integração Nacional, Brasília

Morais Neto JM, Hegarty KA, Karner GD (2006) Abordagem preliminar sobre paleotemperatura e evolução do relevo da Bacia do Araripe, Nordeste do Brasil, a partir da análise de traços de fissão em apatita [Preliminary approach on paleotemperature and evolution of the relief of the Araripe Basin, Northeastern Brazil, based on the analysis of fission tracks in apatite]. In: Geociências, vol 14. Petrobrás, Rio de Janeiro, pp 113–119

Ponce VM (1995) Management of droughts and floods in the semiarid Brazilian Northeast: the case for conservation. Soil Water Conserv J 50:422–431

Ponte FC, Ponte-Filho FC (1996) Estrutura Geológica e Evolução Tectônica da Bacia do Araripe [Geological structure and tectonic evolution of the Araripe Basin]. Departamento Nacional de Produção Mineral, Recife, Brazil

Rede Cooperativa de Pesquisa (2007) Comportamento das bacias sedimentares da região semi-árida do Nordeste Brasileiro: caracterização hidrogeológica [Behavior of sedimentary basins in the semi-arid region of Northeast Brazil: hydrogeological characterization]. Serviço Geológico do Brasil, Fortaleza, Brazil

Rogers S, Chen D, Jiang H, Rutherfurd I, Wang M, Webber M, Crow-Miller B, Barnett J, Finlayson B, Jiang M, Shi C (2020) An integrated assessment of China's South—North Water Transfer Project. Geogr Res 58(1):49–63

Rollason E, Sinha P, Bracken LJ (2021) Interbasin water transfer in a changing world: a new conceptual model. Prog Phys Geogr: Earth Environ. https://doi.org/10.1177/03091333211065004

Shao X, Wang H, Wang Z (2003) Interbasin transfer projects and their implications: a China case study. Int J River Basin Manag 1(1):5–14

Shubo T, Fernandes L, Montenegro SG (2020) An overview of managed aquifer recharge in Brazil. Water 12(4):1072

Shumilova O, Tockner K, Thieme M, Koska A, Zarfl C (2018) Global water transfer megaprojects: a potential solution for the water-food-energy nexus? Front Environ Sci 6:150

Souza AR, Costa AC (2014) Interação rio-aquífero em um rio de médio porte no semiárido cearense [River-aquifer interaction in a medium-sized river in the semi-arid region of Ceará]. In: XII Simpósio de Recursos Hídricos do Nordeste, ABRH, Porto Alegre, Brazil, November 2014

SRH (2022) Cinturão das Águas do Ceará (CAC) [Ceará Water Belt]. Secretaria de Recursos Hídricos (SRH), Governo de Estado do Ceará. https://www.srh.ce.gov.br/cinturao-das-aguas-do-ceara/.. Accessed 6 April 2022

Tortajada C (2006) Human Development Report 2006: São Francisco Water Transfer. United Nations Development Program, Atizapán, Mexico

World Bank (2011) Modelagem Matemática Hidrogeológica do Aquífero Médio e do Aquífero Mauriti da Região do Cariri no Estado do Ceará [Hydrogeological mathematical modeling of the Medium Aquifer and Mauriti Aquifer of the Cariri Region in the State of Ceará]. Governo do Estado do Ceará, Secretaria dos Recursos Hídricos, Fortaleza, Brazil