Groundwater Assessment, Modeling, and Management

M. Thangarajan, Vijay P. Singh

Assessment of Groundwater Resources in Brazil: Current Status of Knowledge

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Assessment of Groundwater Resources in Brazil: Current Status of Knowledge

Fernando A. C. Feitosa, João Alberto O. Diniz, Roberto Eduardo Kirchheim, Chang Hung Kiang, and Edilton Carneiro Feitosa

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3.1 Geological Framework and Tectonic Scenario
The South American continent hosts three large tectonic domains: the Andes, the Patagonic platform, and the South American platform. Exception should be made to a small part of Venezuela that belongs to the Caribbean plate. The South American plate, where Brazilian territory is situated, corresponds to the continental portion of the homonymous plate, which has remained stable as a foreland against the Andean and Caribbean mobile belt and continental drifting during the Meso-Cenozoic period. It has undergone multiple tectonic cycles between the Paleoproterozoic to the Ordovician resulting in a complex framework. Phanerozoic covers have developed since then, setting the beginning of its stabilization phase (CPRM, 2003). The Brazilian orogenic cycle activities lasted up to the Upper Ordovician/Lower Silurian whereby the actual tectonic framework of the Brazilian territory has been built. Microcontinents and continental blocks were transformed giving rise to the actual cratonic areas (Amaú, São Francisco, São Luís, and Paraná) allowing ocean development (Bororema, São Francisco, Goiano, and Adamastor), where a whole set of sedimentary rocks, insular and juvenile continental arc portion shad has undergone metamorphism, deformation, and emplacement of granitic intrusions across multiple events. During its stabilization period, large synecleses have been developed, such as Amazonas (500,000 km²), Solimões (600,000 km²), Parnaíba (700,000 km²), and Chaco-Paraná (1,700,000 km²). Besides the large basins, many small ones were originated (Parecis/Alto Xingu, Alto Tapajós, Tacutu, Recôncavo/Tucano/Jatobá, Araripe, Iguatu, Rio do Peixe, and Bacia Sanfranciscana). Across its continental margin, a great number of mesozoic basins have been developed (Pelotas, Santos, Campos, Espírito Santo/Mucuri, Cumuruxatiba, Jequitinhonha/Camumu/Almada/Jacuípe, Sergipe/Alagoas, Pernambuco/Paraíba, Potiguar, Ceará, Barreirinhas, Pará/Maranhão, Foz do Amazonas, Cassiporé, Marajó, Bragança/São Luís, Barra de São João, and Taubaté). Widespread Cenozoic deposits with heterogeneous thickness cover large portions of the territory. The main units are formation Solimões, Içá, Boa Vista, Pantanal, Araguaia, and Barreiras. The continental area occupied by sedimentary basins is 4,698,050 km², from which 4,513,450 km² (70%) are intracratonic and the remaining 384,600 km² (30%) are lying on the continental margin. Figure 3.1 presents the main basins and sedimentary cover within Brazil. The cratonic areas are composed of plutonic rocks, gneisses, migmatites TTG, and greenstone belts sequences while in the orogenic belts there is a predominance of metasedimentary sequences and intrusive bodies. Some neo-proterozoic and cambri-ordovician basins such as AltoParaguai, Bambuí, Chapada Diamantina, Paranoá, Santo Onofre, Estancia, Rio Pardo, and Jaíbaras, among others contain sedimentary sequences bearing primary structures and low metamorphic grades behaving mostly as fractured aquifers.

3.2 The Hydrogeological Map of Brazil
The hydrogeological map of Brazil, launched by the Brazilian Geological Survey—CPRM/SGB at the end of 2014, represents a synthesis of the hydrogeological information data sets available in the country. It aims at offering an overview of the water well location, aquifer use, and groundwater potential nationwide. It constitutes five main thematic layers.

3.2.1 Planialtimetry Base Map
The planialtimetry base map was obtained from the vector base—1:1,000,000 BCIM/IBGE (Brazilian Institute for Geography and Statistics 2010)—generated throughout the integration of the World International Chart (CIM) with the following information categories: hydrography, landform, political boundaries, transport system, economical structure, energy, communication, reference points, and vegetation.

3.2.2 Geological Database
The geological database was obtained from the GIS Brazil from the CPRM (2003) and based on a simplification of unit attributes and conversion into hydrogeology characteristics, such as groundwater transmissivity and storage.

3.2.3 Tubular Well Database
Data on tubular wells were taken from the SIAGAS—Groundwater Information System, operated and kept by the CPRM/SGB, which is equipped with query modules and report preparation modules. Regarding the hydrogeological map development, a set of 241,692 tubular wells was available for analysis.

3.2.4 Water-Level Database
Water level contour lines based on groundwater level data were developed for the following regional aquifers: Boa...
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FIGURE 3.1
Vista, Itapecuru, Parecis, Guarani, Cabeças, and Uruçuia. These outputs were transformed into potentiometric surfaces using topographical data gathered in the field with GPS. When such data were missing, groundwater level was determined after a digital terrain model (DTM).

3.3 Hydrological Database

The concept of “hydrographic regions” defined by the Water Resources National Council—CNRH has been adopted. The country was divided into 12 main hydrographic regions: Amazônica, Tocantins-Araguaia, Atlântico Nordeste Ocidental, Parnaíba, Atlântico Nordeste Oriental, São Francisco, Atlântico Leste, Atlântico Sudeste, Paraná, Paraguai, Uruguai, and Atlântico Sul.

The hydrogeological potential of each one of the mapped units has been classified according to the contribution of Struckmeier and Margat (1995), who defined six classes (Table 3.1):

1. Very high
2. High
3. Moderate
4. Generally low but locally moderate
5. Generally low but locally very low
6. Nonproductive or nonaquifer

According to this methodology, there are 18 hydrostratigraphic mapping units that have similar storage and transmissibility properties with production classes at the same magnitude order, whose attributes need to be described. The map has also used the International Legend for Hydrogeological Maps developed by UNESCO (1970). Rebouças et al. (1969) and SADC (2009) were also used as important references in this chapter.

The hydrogeological map of Brazil (Figure 3.2) presents an innovative feature dealing with a simplification of the geological background information together with complementary representations of outcropping and nonoutcropping aquifers within its thematic layout. It has been developed within a GIS under a 1:1000.00 scale.

3.4 Paleozoic Sedimentary Basins

3.4.1 Amazonas Sedimentary Basin (1, 2, 3, 7)

The Amazonas Province sedimentary basins (Acre, Solimões, and Amazonas) start at the Andean region where they spread over into the Atlantic coast assuming a fan layout. Their greatest occurrence area corresponds to the flood plains of the Solimões River.

The Acre Basin is situated at the Brazilian territory of the Marañon–Ucayali–Acre Basin, whose total area comprises 905,000 km² (CPRM, 2003), being the most distal part of the sedimentary edge dated between the Cretaceous and the Pliocene. The Iquitos arc acts as its eastern border toward the Solimões Basin. It presents thicknesses up to 6000 m distributed into four supersequences: (i) Permian–Carboniferous, (ii) Jurassic, (iii) Cretaceous, and (iv) Tertiary.

The Permian–Carboniferous supersequence comprises the Apuí Formation, made up of a clastic edge of

<table>
<thead>
<tr>
<th>TABLE 3.1</th>
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<tbody>
<tr>
<td>Productivity Classes</td>
</tr>
<tr>
<td>Q/s (m³/h/m)</td>
</tr>
<tr>
<td>≤4.0</td>
</tr>
<tr>
<td>2.0 ≤ Q/s &lt; 4.0</td>
</tr>
<tr>
<td>1.0 ≤ Q/s &lt; 2.0</td>
</tr>
<tr>
<td>0.4 ≤ Q/s &lt; 1.0</td>
</tr>
<tr>
<td>0.04 ≤ Q/s &lt; 0.4</td>
</tr>
<tr>
<td>&lt;0.04</td>
</tr>
</tbody>
</table>


Q/s = specific yield; Q = flow rate; T = transmissivity; K = hydraulic conductivity.
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DETERMINATION OF AQUIFERS SYSTEMS

Aquifers

Non-aquifers

Intergranular

Flow

Fissured

HYDROGEOLOGICAL MAP OF BRAZIL

FIGURE 3.2
conglomerates, Cruzeiro do Sul, containing carbonates, evaporites, and sandstones (Rio do Moura). The Jurassic supersequence is entirely made up of the Juruna-Mirim formation bearing sandstones and red beds intercalated with evaporites and basal flows, deposited at continental environment. Several formations belong to the Cretaceous supersequence: Moa, Rio Azul, Divisor, and Ramon, which are constituted by sandstones, shales, and calcarenites from fluvialitic-lacustrine environments. The Tertiary supersequence is represented by the Solimões formation with onlap deposition against the basement. Together, they both (the Cretaceous and Tertiary sequences) sum up to 3000 m of thickness (Milani and Zalán, 1998). The Pliocene sandy-clayish sediments of the Solimões formation and the Pleistocene deposits of the Icá formation cover the entire basin.

The Solimões Basin has an area of about 500,000 km² and a total sediment fill of 3800 m, divided by clear marked discordances building up six supersequences (Eiras et al., 1994).

The ordovician and silurian–devonian supersequences comprising, respectively, Benjamim Constant formation (neritic clastic) and Jutai formation (clastic and neritic limestone) are restricted to the Jandiatuba subbasin (Eiras et al., 1994a). The devonian–carboniferous supersequence encompasses the marine sedimentary rocks and glacial–marine rocks from the Marimari group (Uerê and Jandiatuba formation), which outreach the Caruari arc, extending up to the Jurua subbasin.

The carboniferous–permian supersequence is made up of clastic sediments, limestones, marine evaporites, and continental evaporites from the Tefé group (Jurua, Caruari, and Fonte Boa formations). The Cretaceous sequence corresponds to the fluvialitic deposits of the Alter do Chão formation, which are preserved due to the subsidence effects related to the Andean orogeny. Finally, the pelites and the Pliocene sandstones from the Solimões formation constitute the Tertiary supersequence, while the Icá formation is a Pleistocene sedimentation product. The Icá formation is covered by eolic deposits that originate in the Araçá, Anauá, and Catrimâni dune fields. The sedimentary rocks of the Amazon Basin are in onlap form disposition covering basement rocks from the Guianas and the Brasil Central shields, limited by the Solimõesbasin (Purus arc) on the western side and by the Marajóesozoic rift through the Gurupá arc on the eastern side. Total rock thickness reaches 5000 m. Sedimentation begins at the rift phase, with the cambrian–ordovician rocks of the Prosperança formation, basically on analluvial–fluvialite fan environments. The syneclese phase started with the deposition of marine clastic sediments from the Autás-Mirim, Nhamundá, Pitinga, and Manacapuru, arranged in the Trombetas group, belonging to the ordovician–devonian supersequence. The devonian–carboniferous supersequence is composed of the Maecuru, Ererê, Curiri, Oriximiná, and Faro formations, which represent the fluvialitic–deltaic and neritic sediments from the Urupá and Curuá groups. This last one has been followed by a glacial sedimentation period and a posterior depositional gap.

The Tapajós group, constituted by the Monte Alegre, Itaiuba, Nova Olinda, and Andirá formations, has a wide variety of sedimentation environments such as clastic, continental, and marine, building up the Permian–Carboniferous supersequence. This supersequence is followed by the Sanrafaelica orogeny (ca. 260 Ma) and by the Jurua diastrophism. At the very beginning of the Jurassic, an expressive basalt-type magmatism occurred placing Penatecau dikes and flows between the Nova Olinda and Alter do Chão formations. The sedimentation of the Amazonas Basin ceased after the deposition of the continental sequences, one from the upper Cretaceous (Alter do Chão formation) and another Cenozoic (Solimões and Icá formations), generated by a fluvialitic and fluvialitic–lacustrine systems. The groundwater research in this region is still incipient and deals mainly with the Alter do Chão formation aquifer. There is overall information about the Solimões and Icá formations as well (Figure 3.3).

The geologic framework described before and the assessment of the water well logs and oil soundings suggest that the Alter do Chão formation is the main regional aquifer functioning under an unconfined regime. Based on existing data, the Alter do Chão aquifer covers an area of about 410,000 km². Considering a mean thickness of 400 m and an effective porosity of 20%, the saturation volume reaches more than 30,000 km³. According to Souza et al. (2013), even though there are not sufficient data for the estimation of the pressure component, it is clear that this pressure volume is by far much less than saturation volumes, since the parameter S, in confined aquifers, does have magnitudes less than 10⁻⁴. Therefore, in terms of a regional estimation, the saturation volume may be a reasonable magnitude for the aquifer permanent reserve.

Regarding hydrodynamic parameters, the available data that have been taken as references were estimated by Tancredi (1996) for the region of Santarém, at Pará State. According to the author, T ranges from a minimum value of 1.5 × 10⁻³ m²/s and a maximum value of 9.1 × 10⁻³ m²/s. The storage coefficient, S, has values varying from 4.1 × 10⁻⁴ to 3.3 × 10⁻⁴ and finally the K values fall in between 2.1 × 10⁻⁴ and 5.0 × 10⁻⁵ m/s. The hydrodynamic parameters for the Icá-Solimões aquifers are T = 3 × 10⁻³ m²/s, S = 5 × 10⁻⁴, and K = 1 × 10⁻⁴ m/s, whose magnitudes are similar to the minimum values that were determined for the Alter do Chão system, in Santarém. Regarding the Icá-Solimões system, covering an area of 948,600 km², the estimated reserves reach
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7200 km³, less expressive and 22% than the ones found for the Alter do Chão aquifer system. The water quality in almost all aquifers from the Amazonic Basin show generally low contents of cations and anions, with sodium-bicarbonate waters, bearing values for Na⁺ and HCO₃⁻ lower than 7 and 30 mg/L and expressive for K⁺ (maximum concentration reaching 5.5 mg/L). The lower ionic concentrations determine lower values for the electric conductivity, which ranges between 1212 and 100 µS/cm. The groundwater is generally acid and has pH values between 4 and 5.

3.4.2 Parecis Sedimentary Basin (15, 16)

The Parecis sedimentary basin is one of the largest intracratonic basins from Brazil, which is situated at the southwest border of the Amazon craton, assuming an elongated W–E form with 1250-km width. It occupies an area of about 500,000 km² between the latitudes 10° and 15° S and longitudes of 64° and 54° W covering the states of Rondônia and Mato Grosso with almost 6000 m of siliclastic paleozoic, mesozoic, and cenozoic sediments (Figure 3.4). The paleozoic sequence is constituted by the Cacoal, Furnas, Ponta Grossa, Pimenta Bueno, and Fazenda da Casa Branca formation, outcropping on the west, southwestern, and southeastern border of the basin. The mesozoic sequence, on the other hand, formed by the Anari/Tapirapuã and Rio Ávila units and the Parecis group (Salto das Nuvens and Utiariti formations) occurs in the central and western portion of the basin. Finally, the Cenozoic sequence, represented by the detrital–laterite covers belonging to the Ronuro formation and by the quaternary sediments from the Guaporé river, is concentrated in the Alto-Xingú region. The Furnas aquifer constituted by sandstones, conglomerates, and siltstones show productivity classes between 3 and 4 (according to Table 3.1), with low-to-medium productivity, showing specific yields between 0.4 and 2.0 m³/h/m and mean discharge of about 10 and 50 m³/h. The Ponta Grossa formation, composed mainly by pelites (shales, fine sandstones, siltstones, and claystones) belong to class 6 (less productive or nonaquifer). The Pimenta Bueno formation (sandstones, conglomerate, shales, and siltstones), Fazenda Casa Branca formation (conglomerate, arcosean
sandstones, and shales), and Anari/Tapirapuã formation (basalts and diabases) vary according to the productivity classification (Table 3.1) from classes 4 and 6. The Parecis group (sandstones, siltstones, and conglomerate) is considered to be the most important aquifer of the Parecis basin. It is classified as class 1 (very high productivity) showing high values for specific yield, reaching more than $4 \text{ m}^3/\text{h/m}$ and discharges higher than $100 \text{ m}^3/\text{h}$. Finally, the Ronuro formation and the undifferentiated quaternary deposits constituted by sand, clay, and gravel were classified as class 4; nevertheless, due to the fact that they are easily tapped, a great part of the population tends to use them.

3.4.3 Parnaíba Sedimentary Basin

The Parnaíba sedimentary basin occupies an area of about 600,000 km², embracing almost the entire area of the states of Piauí and Maranhão and expressive areas of the Pará and Tocantins States. The São Vicente Ferrer-Urbano Santos-Guamá Arc acts as its northern border, whereas the Tauá fault zone, the Senador Pompeu fault zone, the Tocantins-Araguaia fault zone, and the Tocantins arc are their borders on the eastern, southeastern, western, and northwestern portions. According to Goès and Feijó (1994) the basin hosts four depositional sites: Parnaíba basin, Alpercata basin, Grajaú basin, and Espigão Mestre basin (Figure 3.5). The depositional site called Parnaíba basin covers approximately half of the total area of the entire basin and is situated mainly in the center and southern area (Figure 3.5). It comprises the Silurian supersequences (Serra Grande group), Devonian (Canindé group), and triassic–carboniferous (Balsas group). The Serra Grande group is composed of the Ipu, Tianguá, and Jaicós formation whereas the Canindé group is composed of the Itaim, Pimenteiras, Cabeças, Longá, and Poti formations. The Piauí, Pedra-de-Fogo, Motuca, and Sambaíba formations constitute the Balsas group (Figure 3.5). The Alpercata basin covers 70,000 km² (Figure 3.5) and is composed of the Jurassic supersequence (Mearim group), which is constituted of the Pastos Bons and Corda formations sealed, respectively, at the bottom and the top, by the igneous formations Mosquito (Jurassic) and Sardinha (lower Cretaceous). The Grajaú basin is situated at the northern side of the Alpercata basin and gets isolated from the São Luís basin by the Ferrer-Urbano Santos arc, which does not exert any influence on the sedimentation continuity between both basins. It is filled by the Grajaú, Codó formations and the Itapeuru Grup belonging to the Cretaceous supersequence (Figure 3.5). The Espigão Mestre basin is covered by eolic sandstones and lies discordantly above the Parnaíba basin. It corresponds to the northern part of the Urucuia basin, which is the setentrional part of the Sanfranciscana basin.

The Parnaíba sedimentary basin has the largest groundwater potential in the northeast region of Brazil.
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The multilayered permeable geological strata gives rise to regional aquifer systems in heterogeneous hydraulic regimes, varying from unconfined to confined and sometimes artesian conditions (Figure 3.6). The most important aquifer units are the Serra Grande group followed by the Cabeças and Sambaíba formations and the Poti/Piauí system. The Corda and Itapecuru aquifers show slightly lower potential but a wide geographical distribution within the basin. On the upper part of the sedimentary sequence, one may find the Grajaú aquifer, the Barreira/Pirabas group, and the quaternary cover with low potential for groundwater production. The Serra Grande aquifer represents an extensive and important aquifer unity, which lies discordantly over the crystalline basement. It is constituted by an essentially clastic sequence, with conglomerates and consolidated kaolinite conglomerate sandstones (Ipu formation) followed by arcosean, fine to middle size grained sandstones (Tianguá formation) with conglomerate layers. The sequence ends with clastic pelites, which are situated predominantly in the southern part of the basin. This aquifer extends over 38,000 km² in the eastern, southeastern, and southern border of the Parnaíba basin exhibiting lower potential at its recharge area, a narrow 2–15-km-width fringe. The region under confined conditions shows excellent hydrogeological properties with expressive artesianism regime in some areas. Its thickness varies from 400 to 1000 m. According to the classification adopted by the hydrogeological map of Brazil, the aquifer is classified as class 1, even though its outcropping areas have lower productivity, being classified as classes 5 and 6. The mean hydrodynamic coefficients are $T = 3.0 \times 10^{-3}$ m²/s; $K = 1.0 \times 10^{-5}$ m/s, and $S = 4.3 \times 10^{-4}$.

The Cabeças aquifer is constituted by sandstones with clay material, outcropping over 42,000 km² of the middle
part of the basin reaching a mean thickness of 300 m. It is classified as class 1, similar to the Serra Grande aquifer. Due to the topographical context of their outcropping areas, productivity in those areas is situated between classes 3 and 5; hydrodynamic parameters are $T = 1.3 \times 10^{-2}$ m$^2$/s, $K = 5.4 \times 10^{-5}$ m/s, and $S = 3.7 \times 10^{-4}$ (Feitosa and Demetrio, 2009). The Sambaiba aquifer occurs at the southeastern parts of the Maranhão and northeastern part of Tocantins states, both as an unconfined aquifer and as a confined aquifer as well. It is composed mainly by well-sorted sandstones bearing high permeability and therefore high to very high potential (classes 1 and 2). Its inflow is fed by direct infiltration from rainfall in recharge areas at plain areas covered by unconsolidated sands and by the drainage network. Its principal outlets are the drainage system and evapotranspiration at some aquifer portions richer in clay content.

### 3.4.4 Paraná Sedimentary Basin

The Paraná sedimentary basin is an intracratônica phanerozoic basin established over the Archean and Proterozoic continental crust that is situated in the southern part of the South American platform (Almeida et al., 2000). The stratigraphic register of the basin comprehends a succession of approximately 7000-m thickness of sedimentary and volcanic rocks covering an area of about 92,250 km$^2$. In the largest part of its extension, mainly close to the Parnaíba River, it behaves as an unconfined aquifer whereas toward the middle of the basin it changes to a confined condition. It presents a lithological constitution based on massive sandstones with few intercalations of shale at the inferior part of the sequence. Their recharge originates directly from the rain vertical infiltration, drainage throughout-confining units, and the superficial drainage network. The main aquifer outlets are the drainage system and evapotranspiration at some aquifer portions richer in clay content.
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developed during the neo-Ordovician and the neo-Cretaceous, under marine to continental sedimentation environments (Milani, 2004; Milani et al., 2007). The Paraná basin occupies an area of about 1.1 million km² in Brazil, distributed in eight Brazilian states, complemented by more than 400,000 km² in Argentina, Paraguay, and Uruguay. Within its geological framework, the Paraná basin contains a diversity of sedimentary aquifers with intergranular porosity that has been generated in different depositional environments, such as fluvial, marine, glacial, and desert. The predominant sedimentary processes and the postdiagenetic modifications ended up defining distinct hydraulic characteristics, resulting in different groundwater potential. Among these aquifers, the most important ones are the Tubarão aquifer (SAT), the Guarani aquifer (SAG), and the Bauru aquifer (SAB), whose storage and transmission conditions allow their wide exploitation for fulfilling of domestic, industrial, and agricultural demands. Emphasis should be given to the fractured aquifer developed by the volcanic rocks called the Serra Geral aquifer (SAG). Besides the main aquifers, there are also some aquifers with low permeability, such as the Passa Dois aquiclude, which is composed by a thicker permian sequence disrupting the hydraulic continuity between the SAT and SAG aquifers (Figure 3.7).

3.4.4.1 Tubarão Aquifer System (SAT)
The Tubarão aquifer system has its outcropping areas of about 99,000 km² in a narrow fringe close to the northwestern, eastern, and southwestern borders of the basin. At the subsurface, it spreads over almost the entire basin reaching 750,000 km². It is considered a granular porous aquifer constituted by the Tatuí, Palermo, Rio Bonito, Aquidauana, and Itararé stratigraphic units. Its lithological composition varies a lot, from diacmetites, siltstones, pelites, shales, ritmites, sandstones, and conglomerate sandstones deposited by marine, glacier, coastal, and fluvial processes. It may reach 800 m of thickness in the outcropping areas (DAEE, 2005) and sometimes more than 1000 m in the remaining areas as shown by well drilling logs. The hydraulic conductivities range from $2.31 \times 10^{-8}$ to $8.10 \times 10^{-6}$ m/s (Diogo et al., 1981) whereas transmissivities vary between $3.5 \times 10^{-6}$ and $4.63 \times 10^{-4}$ m²/s. Locally, transmissivity values may reach 150 m²/day (DAEE, 1981, 1982). These values allow this aquifer to be classified as classes 3 and 4. The porosities are generally low in clay sandstones, but may reach up to 30% in sandstones with lower clay content (França and Potter, 1989). The porosity and the permeability of this reservoir are controlled mainly by grain size, grain selection and, secondarily, by the presence of carbonate cementation (Vidal, 2002). The high subsidence rates of this basin during deposition of the SAT unities has also affected the permo-porosity characteristics of the aquifer due to the chemical compaction effect, followed by an increase of the pressure and temperature conditions (Bocardi et al., 2008). Frequent intercalations between coarser and fine sediments, with distinct thicknesses set up a very heterogeneous framework that affects the groundwater storage and flow within aquifer media. (DAEE, 1981; Diogo et al., 1981). The petele lithologies interlayered to the sandstones hinder the groundwater flow downward increasing its heterogeneity where vertical permeability is lower than horizontal permeability (DAEE, 1981; Diogo et al., 1981). The same happens with the frequent diabase sills, with variable thickness, which may affect badly the regional or local flow continuity (DAEE, 1981). At small depths, the SAT behaves generally as an unconfined aquifer (DAEE, 1981). At the outcropping areas, the permeable sediments receive direct recharge from rainfall and they do discharge expressive amounts of water into the fluvial network. Besides its expressive thickness, the SAT is being exploited by tubular wells not deeper than 300 m, extracting moderate yields between 10 and 20 m³/h (Diogo et al., 1981). The groundwater tends to be slightly saline, with total dissolved solids content between 100 and 200 mg/L and being classified as sodium bicarbonate or calcium bicarbonate (DAEE, 1984). Under extreme confined conditions, in depths more than 400 m, the groundwater may present elevated saline concentrations, above potable thresholds. This is why it is not being intensively exploited thus far.

3.4.4.2 Guarani Aquifer System (SAG)
The SAG is the most important hydrostratigraphic unit from the southern part of the South American continent and is considered to be one of the world's largest transboundary aquifers, extending across wide territories of Brazil, Argentina, Paraguay, and Uruguay. The largest part of the aquifer is situated in Brazilian territory comprising 736,000 km². The outcropping areas reach only 88,000 km² and are situated along the basin border as a narrow belt whereas the confined areas, covered by volcanic sequences, sum up 648,000 km² (OEA, 2009). The SAG is constituted by a sequence of mesozoic continental clastic rocks within the Paraná basin, being delimited by a regional permo-triassic discordancy (250 million) at the base and by volcanic flows from the Serra Geral formation (145–130 million) at the top. In almost all compartments of the basin, the stratigraphic units that constitute the SAG are, exclusively, the Piarambóia and Botucatu formations. Nevertheless at the southern parts of the basin, the SAG is also locally represented by the Santa Maria, Caturrita, and Guará formations (Machado and Faccini, 2004). The SAG framework comprehends
predominant eolic continental deposits represented by fine-to-medium-size sandstones exhibiting large-size cross-stratification and secondarily fluviatile lacustrine sandstones and sandy pelites (Caetano-Chang, 1997). At the southern compartment of the basin, there is a basal succession composed of sandstones and pelites deposited by a fluviatile lacustrine system (Machado, 2005; Soares et al., 2008). In almost the entire basin extension, the SAG sequences are layered on top of thick permian units of low permeability, which integrate the Passa Dois aquiclude. At the western part of the basin, the SAG covers carbo-permian sediments of the Aquidauana formation (LEBAC, 2008). The thickness of the SAG increases gradually from outcropping areas, where they are only partially preserved, to the main axis of the basin. At the northern region, there is an elongated depocenter parallel to the main basin axis that accumulates a sediment thickness of 600 m (LEBAC, 2008). Close to the internal tectonic arcs (Ponta Grossa arc and Rio Grande arc) and to the Torres sinclinal, the thicknesses get drastically smaller until they are less than 100 m (LEBAC, 2008). At the eastern compartment of the basin, where there is an intensive groundwater exploitation, SAG thickness varies from 100 m at outcropping areas to 400 m toward the basin major axis (DAEE, 2005). Generally, the mean thickness of the SAG ranges between 200 and 250 m.
its largest part, SAG is covered by about 1700 m of volcanic rocks (LEBAC, 2008). The SAG eolic sandstones have mean porosities of 20% up to 30%, but fluvial ones may show lower values (OEA, 2009). The conductivity of the aquifer has been estimated at 2.6 m/day for the confined areas and 3.0 m/day at the unconfined areas (DAEE, 2005); transmissivity has been estimated at $3 \times 10^{-3}$ m$^2$/s for the outcropping areas and more than $1.4 \times 10^{-2}$ m$^2$/s for the confined areas (DAEE, 2005). The storage coefficient varies between $10^{-3}$ and $10^{-5}$ (DAEE, 1974). Due to the faciological features of the main hydrostratigraphic units of the SAG (Botucatu and Pirambôia formation) and the shallow burying history, the diagenetical modifications were not efficient enough to change original poro-porosity of these rocks (Gesicki, 2007). On the other hand, diluted water inflows, acting in depths up to 250 m within SAG layers, have removed carbonate cement and have leached feldspatic grains giving rise to a secondary porosity (França et al., 2003). The unconfined aquifer potentiometry reveals local and regional flows, being ruled by the topography within the hydrographic basin in the first case and from outcropping areas dipping toward the interior parts of the basin under confined flow regime. From there on, the aquifer remains mostly confined where in regional terms, flow tends to be from north to south, following the main basin axis (LEBAC, 2008). In some specific areas, water levels go far beyond surface levels building artesianism. The SAG presents excellent potentials, turning it into a stratigraphic reservoir for satisfying water demands at small- and medium-sized cities. At the outcropping areas, well discharges are about 80–100 m$^3$/h whereas in the confined areas, they yield more than 200 m$^3$/h with specific capacity varying from 2 to 15 m$^3$/h. The recharge rates of the SAG, from 1 to 3 km$^3$/annual, are very small considering its extension (OEA, 2009) and extraction volumes for a variety of uses. In both situations, it is considered to be class 1 in terms of productivity. The hydrochemistry of the SAG shows different patterns depending on the aquifer flow regime. At the outcropping areas with unconfined regime, the water tends to be calcium bicarbonate with low electric conductivity. At the confined areas, in the other side, waters are sodium bicarbonate with higher mineralization degree. At the main basin axis, the groundwater tends to be sulfate, sodium chlorinated highly mineralized, however, and presenting great possibility of mixture with water originated in underlying formations.

3.4.4.3 Serra Geral Aquifer System (SASG)

The Serra Geral Aquifer System spreads over an area of about 735,000 km$^2$ within the Paraná basin, from which 409,000 km$^2$ constitutes outcropping areas of the Serra Geral formation. These volcanic sequences are partially covered by the sediments of the Bauru group and they may reach almost 1700 m of thickness at the main basin axis. Due to their wide spatial distribution, this system is considered to be an important groundwater reservoir with capacity to fulfill small-to-medium-size demands and work as a complementary water source. The storage and flow of the water occur through physical discontinuities such as fractures, faults, and interflow surfaces, which constitute a heterogeneous, anisotropic, and discontinuous media (Rebouças, 1978). The fracture systems are related to tectonic stresses and also to cooling processes generating subvertical and subhorizontal fractures, respectively (Campos, 2004; Lastoria et al., 2006). Water extraction is done through wells with 100–200-m depth, which allow yields varying from 100 m$^3$/h (when intercepting productive fracture systems) to null, a situation that may happen very often. The relationship between water yield and linear density proved to be weak according to studies carried out by DAEE (2005). The explanation given is that subhorizontal surfaces such as lava spill contacts do have an important influence controlling water flow, but are not detectable by remote-sensing techniques. The water from the SASG is mainly calcium bicarbonate and secondarily calcium–magnesium bicarbonate and sodium bicarbonate with saline contents less than 250 mg/L (Campos, 2004). According to the classification scheme adopted, these aquifers fall between class 2, in clearly confined scenarios, and 6 due to their topographic setting.

3.4.4.4 Bauru Aquifer System (SAB)

The Bauru Aquifer System comprehends a succession of Cretaceous sedimentary rocks that were deposited over 370,000 km$^2$ of the center-setentrianal part of the Paraná basin covering the basalt floods of the Serra Geral formation. Its mean thickness is 100 m, but it may reach 300 m in certain sectors of the basin. Due to the fact that it is a superficial aquifer, well drilling gets easier and exploitation costs are low. On the other hand, it shows high vulnerability toward inorganic and organic contaminant leakages (DAEE, 1976, 1979). The SAB is a multilayered hydrostratigraphic system composed of the Marília, Adamantina, Birigui, Santo Anastácio, and Caiuá aquifers and the aquitards Araçatuba and Pirapozinho (Paula and Silva, 2003, 2005). The sedimentation environments of these aquifers are mainly fluviatile with eolic interactions. The aquitards relate to pelites developed at lacustrine environment (Paula and Silva, 2005). Their hydrodynamic behavior is heterogeneous according to their lithological framework in which sediments with different porosities and permeabilities share lateral and vertical contact relationships. Consequently, the
registered yields in these aquitards are variable (Paula and Silva, 2003). The SAB is considered to have moderate permeability according to its clay and silt contents and to the presence of less permeable and impervious layers along the profile (DAEE, 1976). The conductivities in the SAB range from $2.31 \times 10^{-8}$ to $4.24 \times 10^{-5}$ m/s whereas the transmissivities vary from $1.62 \times 10^{-6}$ to $3.8 \times 10^{-3}$ m$^2$/s. Values lower than 50 m$^2$/day are very often the case (DAEE, 2005). In areas where sedimentation is predominantly eolic, clearly sandy, the transmissivities reach far beyond 200 m$^2$/day (Iritani et al., 2000). The effective porosities are about 5% in clayish sandstones and between 10% and 20% in sandstones with less clay (DAEE, 1979). These hydraulic characteristics set up exploitable yields that start at 10 m$^3$/h and reach up to 120 m$^3$/h. Discharges more than 80 m$^3$/h, however, are not recommended (DAEE, 2005). Multilayered aquifer systems or single confined aquifer units, such as the SAB, may exhibit more than one potentiometric surface, which reflects the equilibrium among different aquifer unit hydraulic charges. So, at one single place, one can recognize an unconfined potentiometric surface, at shallow depths, and a deeper confined one (Paula and Silva, 2005). The aquifer unconfined potentiometric surface is ruled by the groundwater flow within the watershed. The water from the SAB is calcium to calcium–magnesium bicarbonate and more rarely sodium bicarbonate (Coelho, 1996; Celligoi and Duarte, 2002; Barison, 2003). Stradioto (2007a,b) has also found the presence of calcium chloride–sulfate and sodium chloride–sulfate water. Generally, the SAB presents lower saline concentration with dry residue showing values rarely higher than 300 mg/L (DAEE, 2005).

3.5 Mesozoic and Meso-Cenozoic Sedimentary Basin

In respect to their strategic importance for the semi-arid region in Brazil, among all the Mesozoic and Meso-Cenozoic basins, only the ones situated in the northeast area of the country are going to be emphasized (Figure 3.1).

3.5.1 Potiguar Basin

This basin is located in the north coast of the state of Rio Grande do Norte and southeast of Ceará state. Its entire extension comprises an area that can vary between 41,000 and 60,000 km$^2$, including its outcropping and subsurface portions. The main aquifers are represented by the Jandaíra and Açú formations. The aquifer Açú, whose thickness varies between 400 and 700 m, corresponds to the inferior portion of the Açú formation and is constituted by sandstones and conglomerate at the lower portion of the sequence evolving gradually to fine sandstones at the upper part of the sequence. It is perceived as the most important groundwater storage system within the Potiguar Basin.

The outcropping areas are situated along a marginal belt whose widths vary from 5 km at the eastern side to 20 km at the western corner. The first deep well drilled in this aquifer was in 1967 and has revealed artesian conditions, discharging about 80 m$^3$/h of excellent water quality. This favorable scenario was followed by an intense economic development of the region and increase of the water demand due to agro-industrial plants based on irrigation schemes. The Açú aquifer exploitation has been accelerated since the 1970s, reaching overall discharge rates of about 42 hm$^3$/year generating expressive drawdowns of more than 160 m in the most critical areas. Despite the fact that there is a vertical drainage from the limestone above, studies are still not conclusive thus far. The incontestable fact is that the discharge increase has triggered the deepening of the groundwater levels depleting the storage capacity of the aquifer. Meanwhile admitting that the CAERN (Water and Sewage Company of the State of Rio Grande do Norte) has slowed down the use of this aquifer for domestic purposes and that irrigation plants have started to use water from the Jandaíra Aquifer, the potentiometric depression tends to recover. However, the Açú aquifer will always play an important and strategic role in providing low cost solutions. It normally shows high magnitudes of yield allowing it to be classified as productivity class 1. Mean hydrodynamic parameters are $T = 2.3 \times 10^{-4}$ m$^2$/s, $K = 7.5 \times 10^{-6}$ m/s, and $S = 1 \times 10^{-4}$. The Jandaíra aquifer must be addressed in the limestone.

3.5.2 Araripe Basin

The Araripe basin is situated in the states of Ceará, Pernambuco, and Piauí and covers an area of about 11,000 km$^2$. It can be divided into two different sectors: Araripe Highlands and Cariri Valley. Almost the entire groundwater exploitation takes place inside the valleys with few water wells on the highlands. The most important aquifers are the Mauriti and the Batateira/Abaiara/Missão Velha system. The Mauriti aquifer is constituted by a uniform sequence of coarse-grained sandstones, generally silicified, contributing to significant losses of primary porosity. In this case, groundwater flow is controlled by the secondary porosity (fractures and faults). In general, they show only a moderate potential with thickness about 100 m.
Discharge from wells is low (<5 m³/h), excepting fault zones, where yields tend to be much higher. The Rio da Batateira/Abaiara/MISSÃOVelha system is constituted by course to fine size sandstones with siltstones, claystones, and shales, at the intermediate to upper part of the sequence reaching 500 m of thickness. Actually, it is the most used aquifer in the region with yields yielding up to 300 m³/h. Recent studies carried out by the CPRM and the Federal University of Ceará had proposed for the Cariri valley (including the both aquifers) the following estimates: 360 million/m³ of renewable resources, 14 billion/m³ of permanent resources, 450 million/m³/year of exploitable resources, and availability of 54 million/m³/year.

### 3.5.3 Interior Basins

#### 3.5.3.1 Iguatu/Malhada Vermelha/Lima/Campos Icó Basins

At the southeast of the Ceará state, there is a group of small basins situated between the Iguatu and Icó cities, occupying an area of approximately 1000 km². The sedimentation within these basins is mainly clastic with pelite intercalations composing the following aquifer unities: Icó, Malhada Vermelha, and Lima Campos. On top of them, there are some unconsolidated clastic formations that may exhibit groundwater storing capacity. Well drilling is done intercepting all these aquifers at depths lower than 100 m. However, the exploitation in this region is still small due to the large hydraulic availability imposed by the Orós Lake. There is no well deeper than 100 m and underground information has been generated by geophysical assessments. The aquifers show a small hydrogeological potential delivering yields of about 3 m³/h. The greatest potential remains in the banks of the Jaguaribe River where reservoirs may have 25 m of thickness and 500 m of width. The high conductivities shown by these alluvial bars allow expressible groundwater extraction fulfilling water demands of Iguatu City.

#### 3.5.3.2 Lavras da Mangabeira Basin

This represents a group of small basins situated in the southeast region of the Ceará state covering an area of about 60 km². The Serrote, Limoeira, and Ibroipi formations show groundwater potential. Assessments carried out by the CPRM and the Federal University of Ceará (CPRM/UFC, 2008b) indicates 4.6 million/m³/year of potential and an installed availability of 1 million/m³/year. The greatest part of this volume is used by the state-owned water company CAGECE for public supply.

#### 3.5.3.3 Coronel João Pessoa/Marreca and Pau dos Ferros Basins

These small basins with total area of 16, 27, and 65 km², respectively, are situated in the west side of the state of Rio Grande do Norte. They are constituted by fine-to-coarse-grained sandstones, siltstones, and claystones from the Antenor Navarro formation. Despite the existence of data, through an analogy with other similar sequences, one may estimate that they bear reasonable groundwater potential at their sand-rich zones.

#### 3.5.3.4 Rio do Peixe Basin

This basin is located at the far northwest side of the Paraíba State covering an area of 1300 km². Sedimentary filling comprises the coarse-to-fine sandstones of the Antenor formation, the siltstones, shale, and calciferous sandstones of the Souza formation, and the fine sandstones and conglomerates of the Rio Piranhas formation. This stratigraphic profile conditions the existence of two major aquifers, namely, the Rio Piranhas and the Antenor Navarro, separated by the Souza aquitard. Recent studies developed by the Brazilian Geological Survey in partnership with the Federal University of Campina Grande (CPRM/UFGC, 2008) led to significant advances in the understanding of the groundwater flow network within the basin. The reserves estimates had not been calculated because there are still some incongruences concerning aquifer geometry. Both aquifers show a small potential with yields of about 10 m³/h.

#### 3.5.3.5 Cedro Basin

This basin is situated at the northwest corner of the state of Pernambuco and has an area of 168 km². The most important aquifer is represented by the Mauriti formation, whose hydrogeological behavior was already described. Detailed information is still missing but expectations converge to moderate groundwater potential.

#### 3.5.3.6 São José do Belmonte Basin

It is situated at the center–north of the Pernambuco state and has an area of 755 km². The predominant aquifer is the Tacaratu formation composed of heterogeneous medium-size-to-coarse sandstones with kaolinite levels and strong diagenesis. It shows a very heterogeneous hydrodynamic behavior, where secondary porosity prevails over the primary one. As a consequence of that, a wide discharge magnitude variation occurs (starting at 1 m³/h to more than 50 m³/h). Besides the existence of more than 1000 wells registered by the CPRM, the knowledge on the aquifer is still very incipient.
3.5.3.7 Mirandiba/Carnaubeira/Betânia and Fátima Basins

These basins are located in the center portion of the state of Pernambuco and present the following dimensions: 143, 136, 280, and 270 km², respectively. Their hydrogeological potential is given by the Tacaratu formation, which is constituted by medium-to-coarse heterogeneous sandstones with kaolinite levels and strong diagenesis as well. In the outcropping areas, groundwater behavior is similar to the Mauriti aquifer. The knowledge is still very incipient, but potential is expected to be moderate to low. Tubular wells completed by the Brazilian Geological Survey in the Fátima basin with depths starting at 300–420 m delivered yields of 30 and 100 m³/h, respectively.

3.5.3.8 Recôncavo/Tucano/Jatobá Basins

The sedimentary basins of the Recôncavo and Tucano cover an area of about 50,000 km² across the coastal areas of the Bahia State and Pernambuco. In these two basins there are three major aquifer systems: (i) the upper aquifer represented by the Marizal and São Sebastião formations; (ii) the intermediate aquifer represented by the Ilhas Group and Candeias formation; and (iii) the lower aquifer represented by the Sergi and Aliança formation. The upper aquifer system is the most exploited one and the São Sebastião formation is the most productive unit with wells reaching up to 100 m³/h and thickness of 3000 m. This aquifer is responsible for the water supply of the Camaçari petrochemical plant, where a strict water-quality monitoring control is taking place. There is no consistent data on stored volumes, mainly in the intermediate and lower aquifers. In general, one can assume a moderate to high hydrogeological potential with wells having a specific capacity of 3 m³/h/m. Until 800 m the water is considered to be of good quality. The Jatobá basin is situated in the central region of the Pernambuco and northeast of the Alagoas state, covering 5941 km². It shows an excellent hydrogeological potential represented by the Inajá/Tacaratu aquifer system. This system is constituted by a sequence of coarse-grained sandstones with pelite intercalations at the base (Tacaratu formation) and fine, ferruginous sandstones with siltstones intercalations at the upper part (Inajá formation). Thickness estimates reach about 500 m for the entire sedimentary sequence, whereas 350 m refers to the Tacaratu formation and 150 m to the Inajá formation. Studies carried out by the Brazilian Geological Survey together with the Pernambuco Federal University revealed reserves of about 6.192 hm³ (only for the areas under unconfined behavior regime), renewable resources in order of 3.1 hm³/year, potential about 12.4 hm³/year, installed availability of 0.7 hm³/year, and exploitable resources of about 9.3 hm³/year for the next 50 years (CPRM/UFPE, 2008). The groundwater resources are being used for the supply of the surrounding cities (Sertânia and Arcoverde in Pernambuco state).

3.5.3.9 Sanfranciscana Basin/Urucuia Aquifer

The Urucuia Aquifer, in the context of the Sanfranciscana basin, covers territories of six different states of Brazil (Bahia, Tocantins, Minas Gerais, Piauí, Maranhão, and Goiás) and occupies an area estimated as 120,000 km². The greatest area, 90,000 km² occurs in the western side of the Bahia State. For a long time, due to the lack of information, the Urucuia Aquifer has been considered a low hydrogeological potential unit. However, recent studies have shown that wells with 250–300-m depths delivering up to 500 m³/h and bearing specific capacity higher than 10 m³/h/m are frequent. From a lithological point of view, they are represented by a succession of friable fine-to-coarse-size kaolinite sandstones with conglomerate levels reaching thickness of 600 m. It acts as the watershed boundaries between the São Francisco river at the east, the Tocantins river at the west, and the head of the Parnaíba river at the north. Under such conditions, it is expected that the aquifer exerts an important role keeping basal flow in those rivers, a scenario where the integrated water resources management concepts are crucial. In the last few years, the aquifer exploitation has risen vertiginously following the accentuated expansion of irrigated agriculture. Aquifer knowledge is still insufficient and restricted to pilot areas after studies carried out by the Brazilian Geological Survey, the Water Resources Secretary of the Bahia State, and universities. The unconfined characteristics of the Urucuia Aquifer make it the largest groundwater reservoir in the Bahia State and one of the largest within the entire country. Gaspar (2006) has estimated permanent and renewable reserves in $3 \times 10^{12}$ m³ and $3 \times 10^{10}$ m³/year, respectively. The exploitable reserves were estimated to be $4 \times 10^{11}$ m³.

3.6 Limestone

Karstic limestone formations are always or nearly always present in all Brazilian sedimentary basins with varying degrees of economic interest both as groundwater reservoirs and as raw material for the cement industry. The most extensive water-bearing limestone formations occur, nevertheless, in Neo-Proterozoic terrains, in the states of Bahia and Minas Gerais, within the drainage basin of the São Francisco River. Overall, four major hydrogeologic karstic provinces may be recognized in
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Brazil, at the current stage of knowledge. These are (1) Jandaira Aquifer, in the Cretaceous Potiguar Basin, state of Rio Grande do Norte, northeast Brazil; (2) Pirabas Aquifer of Tertiary age, in the sedimentary coast basin of the state of Pará, north Brazil; (3) the Una Group of Neoproterozoic age, in the north of the state of Bahia; and (4) the Bambuí Group of Neoproterozoic age, in the west of the states of Bahia and Minas Gerais.

3.6.1 Jandaira Aquifer

The Jandaira Formation is a sedimentary marine deposit made mostly of carbonate rocks whose thickness may attain 600 m in some places of the Potiguar Basin, such as the valley of the Mossoró River. The formation traces back the widespread marine transgression which closed the Cretaceous sedimentary history of the Potiguar Basin in the north coast of the state of Rio Grande do Norte (Figure 3.8). Karst structures such as solution channels, caves, and sinkholes developed in the upper 80 m of the formation, giving place to the so-called Jandaira Aquifer. Although occurring all over the Potiguar Basin, this aquifer shows its uppermost expression in the region west of the Apodi River known geologically as Platform of Aracati. There, since the early decade of 1990, the Jandaira Aquifer has been giving extensive support to fruit crops such as melon, pineapple, papaya, and others, mainly for exportation to Europe and the United States. Recent studies carried out by the Brazilian government counted about 2000 wells in the Platform of Aracati, with depths in the range of 60–120 m, and discharges commonly vary from 10 to 70 m³/h. Discharges from 70 to 250 m³/h also occur although less frequently. The groundwater storage, namely, the water table, is very sensitive to the recurring droughts that affect the region, which may cause serious water crises, when a great number of wells can go dry. In the year 2002, the fruit crops, which are the basis of the economy of the region, were impacted strongly by such a crisis. Nevertheless, the typical karstic landscape with sinkholes densely scattered all over the surface area greatly improves the response of the water table to infiltration in years when precipitation is above the annual mean value of 700 mm. On occasion, one or two very generous rainy seasons may provide the replenishment of the reservoir to what its reserves were prior to the draught period. In this way, the water table of the Jandaira Aquifer, as well as its reserves, seems to undergo a long-term fluctuation whose behavior is to be better understood for the sake of groundwater management in the region. In the year 2010, 244 hm³/year were being extracted, which represented 41% of the renewable resources, estimated as 591 hm³/year with a 50% chance (Oliveira et al., 2012).

3.6.2 Pirabas Aquifer

Although present all over the coastal region of the Pará State, the main area of occurrence of the Pirabas Formation is the region west of Belém City. This area measures about 24,000 km² and is known geologically
as the Bragintina Platform (Figure 3.9). The Pirabas Formation, of Tertiary age, shows two distinct sections. The upper section is made up of limestone and marls with intercalations of black and greenish-gray shale and carbonate sandstones. Light-gray sandstones dominate in the lower section.

The Upper Pirabas Aquifer developed in the upper section of Pirabas Formation, in depths between 70 and 180 m. Wells can yield up to 200 m³/h being, nevertheless, very expensive, which makes drilling accessible only to government or big industries (Matta, 2002). Quite preliminary studies suggest groundwater storage of about 400,000 hm³. The discharge being recovered is something around 100 hm³/year corresponding to 0.03% of the groundwater storage. No data are available yet on renewable resources. The Lower Pirabas Aquifer developed in the lower section of Pirabas Formation, in depths within the range of 180–280 m. Wells may produce as much as 600 m³/h of excellent potable water (Matta, 2002). Due to excessive costs of drilling, though, this aquifer is little exploited.

3.6.3 Salitre Aquifer

The Salitre Formation, of the Neo-Proterozoic age, is the most important formation in the Una Group, in the state of Bahia. It spreads itself over an area of about 38,000 km² forming four separate bodies. The most important of them is the so-called Basin of Irecê. The dominant lithology is black-to-gray limestone exhibiting a certain degree of metamorphism. Tectonic style goes from near-horizontal layers, in the region along the rims of the basin, to folded layers striking E–W and dipping near vertically in the central regions. The Una Group is physically separated from the Bambuí Group by high ridges sculptured in Proterozoic quartzites. The Salitre Aquifer corresponds to karst structures which are widely developed in the Salitre Formation to depths up to 80 m. About 20,000 wells this deep are reported to exist in the Irecê Basin giving support both to agriculture and public supply. As with the Jandaira Aquifer, climate hazards affect seriously on occasion the economy of the region. Nowadays the Brazilian Water Agency is undertaking hydrogeologic studies in the karst provinces of the São Francisco Basin, aiming at the knowledge of the amount of water being withdrawn from the aquifer and being recharged to it. The main goal of the studies is to establish a groundwater budget in order to assess the sustainability of groundwater exploitation in the near future.

3.6.4 Bambuí Aquifer

The Bambuí Group, of Proterozoic age, is composed of five geological formations (Três Marias Formation,
Serra da Saudade Formation, Lagoa do Jacaré Formation, Santa Helena Formation, and Sete Lagoas Formation), which occur in the states of Bahia, Minas Gerais, Goiás, and Tocantins, spreading itself over an area of about 120,000,00 km² (Figure 3.10). Excepting the uppermost Três Marias Formation, all the other formations of the Bambuí Group include carbonate rocks in greater or lesser amounts. The term Bambuí Aquifer, therefore, applies to the water-bearing karst structures developed in the various formations of the Bambuí Group. The formations Sete Lagoas and Lagoa do Jacaré, particularly, are the ones mostly made up of limestone. In this way, these formations are the most susceptible to development of karst structures. Due to the variation in the carbonate content of the formations of the Bambuí Group, groundwater storage and availability in the Bambuí Aquifer varies widely throughout its domain of occurrence. The Bambuí Aquifer has

FIGURE 3.10
Una and Bambuí Groups in the basin of the São Francisco River.
become of utmost importance in providing support to irrigation and public supply in the states of Bahia and Minas Gerais, mainly in times of droughts. Prolonged droughts, however, such as the one the region is undergoing, impact the economy and public supply in exactly the same way as with the Jandaíra Aquifer. The lack of knowledge concerning withdrawals and recharge brings about incertitude as to sustainability of groundwater exploitation in the future. The Brazilian Water Agency is carrying out extensive studies to provide better knowledge on the matter.

3.7 Pre-Cambrian Crystalline Basement

In the crystalline region of the Brazilian semiarid, where there is practically no weathering cover, the groundwater flows through interconnected rock fracture and discontinuity systems, building up reservoirs with limited extension. Considering a certain control volume of rock, which is representative of the whole rock mass of the basement region, there are “n” discontinuity systems, independent among themselves, but with the ability to store and transmit water. Manoel Filho (1996) introduced the concept of hydraulic conductor (HC), in order to define the interconnected fracture systems that are associated with a certain well and that represent the water storage and production at crystalline rocks. Therefore, the fissured aquifer would be the sum of all existing HCs within an area, being represented as

\[
\sum_{i=1}^{n} CH_{i}(X,Y,Z)
\]

where X and Y are location coordinates and Z is the depth of the well.

At crystalline rock terrains, the water prospection approaches still miss deeper technical affirmation. A great number of unsuccessful drillings or wells bearing saline water are still taking place. There are no conceptual models strong enough to fully sustain well location and exploitation and the variables conditioning groundwater quality and quantity. The utilization of these water sources is always associated with risk components to the extent that the groundwater-sustainable yields and overall reserves cannot be safely estimated still. Despite this, since the early 20th century, in the entire northeast region, there is a great number of water wells discharging uninterruptedly. In many cases, unconfined aquifer characteristics and the high hydraulic conductivities associated with fracture systems allow a direct and prompt recharge that keeps permanent exploitation conditions which, in turn, are only disturbed under long periods of drought. The major restrictive factor, for instance, for the use of groundwater resources within this region, is the quality. In general, waters are sodium chlorinated and show total dissolved solids above potable limits. The issue regarding the high heterogeneity and anisotropy of the fractured media depends directly on the assessment scale. At a punctual scale, practically, every single well may represent a single aquifer, which may differ from other ones. The differences in quantity and quality between neighboring wells, which intercept distinct HCs, are surprising. Regionalization approaches, dealing with fractured aquifer data sets, therefore, are not consistent. However, for smaller scales (≥ 1,000,000) it may be possible to establish some zones showing similar tendencies regarding determined variables. Figure 3.11 shows 18,600 determinations of electrical conductivity of the groundwater found in fractured aquifers in the states of Ceará, Rio Grande do Norte, Paraíba, and Pernambuco. Each source is classified according to conductivity values, chosen for expressing water quality in terms of salinity: freshwater (CE ≤ 500 µS/cm), brackish water (1000 µS/cm < CE ≤ 2500 µS/cm), and salt water (CE > 2500 µS/cm).

It can be clearly seen that there are zones with different water qualities.

Water classified as brackish appears in the form of contour belts between fresh and salt water. A generic assessment suggests that there are four large zones: Zone 1—predominantly freshwater (southeast coastal area); Zone 2—predominantly salt water (a northeast-southwest range); Zone 3—predominantly freshwater (midwest); and Zone 4—predominantly salt water (north-northwest). Regarding quantity issues, every attempt at reserve evaluation would be mere speculation. However, it is believed that the quantities that can be extracted from fractured aquifers are enough to supply great parts of the diffuse-located population within the semiarid region of Brazil. The occurrence area of the basement rocks in the northeast region is about 750,000 km² and alone in the region called the drought polygon, the area would be 600,000 km². Considering the hypothesis of the existence of one single working tubular well in each 5-km² cell, there would be a total number of 120,000 wells exploiting groundwater resources within this region. The average depths of the wells are 60 m and the mean yields are situated between 1 and 3 m³/h. Statistically, yield distribution assumes a lognormal model, with median oscillating around 1 and 2 m³/h. Möbus et al. (1998) found the value of 1.7 m³/h for the yield of
Assessment of Groundwater Resources in Brazil

Adopting the lower value found for the median, that is, 1 m$^3$/h, and admitting a pumping regime of 6/24 h (considered low), the daily quantity of water delivered would be 720 million L/day, supplying 3.6-million inhabitants at a daily consumption rate of 200 L/inhabitant/day. However, according to the assessment done by the Brazilian Geological Service, the percentage of freshwater within this region is about 20%-30%, reducing the production of freshwater drastically. The most important factor that hinders groundwater use within this region is given by quality constraints. At the southeast area, the existing water boreholes tend to have depths between 100 and 150 m due to the occurrence of thick-weathering covers. The yields are higher than in the northeast, averaging about 5–10 m$^3$/h and delivering water of good physical and chemical quality (Feitosa and Feitosa, 2011).

3.8 Use of Groundwater in Brazil

The urban and rural population growth together with an expressive expansion of agriculture and industrial activities experienced by the nation have led to a remarkable increase in the use of groundwater. There is a close spatial connection between population growth and quality and quantity availability. Groundwater potability can be analyzed after electrical conductivity values because that directly reproduces the dissolved salt content of samples for the whole country, as it was represented in the hydrogeological map of Brazil (Diniz et al., 2014). A great part of the Brazilian territory shows water of excellent quality (electrical conductivity <150 µS/cm), mainly at the north and midwest. Similar to this one, other regions, such as the south and the southeast and the northeast states of Maranhão and
Piauí, do have good water quality (electrical conductivities between 150 and 500 µS/cm) suitable for all kinds of uses. These low saline content zones coincide with the major Paleozoic basins (Amazonas, Parecis, Paraná, and Parnaíba). Besides them, low electrical conductivity values are also found within the Urucuia Aquifer at the borders with the states of Bahia and Goiás, Tocantins and Maranhão, and Piauí. Areas with high saline contents are found at crystalline areas in the northeast region of the country. Waters bearing intermediate quality are found at the Recôncavo—Tucano-Jatobá Basin and Potiguar and Araripe Basin as well. Figure 3.12 illustrates the spatial distribution of the electrical conductivity values for the entire country. Analyzing Table 3.2 it is clear that in many areas of the northern and midwestern regions, despite the good groundwater quality, well density is very small due to the low urban density development and enormous superficial water availability. The northeast region of semiarid climate conditions, which encompasses large regional capitals such as Recife, Fortaleza, Natal, Joao Pessoa, and Maceió, some of them partially supplied with groundwater, present the greatest well density of the country—more than 50% of registered wells consuming 41% of the total volume of extracted groundwater in the entire country.

Although these waters are frequently saline, they still represent the only available water source. From a general overview, the largest groundwater exploitation takes place at the coastal areas, increasing toward the east and south, coherent with the main urbanization and industrialization axis of the country. The overall volumes according to each region in the country are found in Table 3.2.

![Distribution of the electrical conductivity in Brazil](image-url)
Table 3.2
The Use of the Groundwater in Brazil

<table>
<thead>
<tr>
<th>Geographic Region</th>
<th>State</th>
<th>Area (km²)</th>
<th>Number of Wells</th>
<th>Wells/10 km²</th>
<th>Brazil (%)</th>
<th>Annual Volume Exploited (m³)</th>
<th>Brazil (%)</th>
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<td>Norte</td>
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References


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