Rain dance

The water shortage alarming Brazil is closely related to its forests

TEXT **Maria Guimarães** PHOTOS **Léo Ramos**

PUBLISHED IN DECEMBER 2014

Changes in the volume and frequency of rainfall and the misuse of water supplies are among the factors drying up the pipes in parts of Brazil

The Amazon is not just the largest tropical rain forest remaining in the world. This endless span of green intersected by winding rivers of varying sizes and colors is also not just the home of an incredible diversity of animals and plants. The Amazon rain forest is also an engine capable of changing the direction of the winds and a pump that sucks water from the air over the Atlantic Ocean and the soil, circulating it over South America and carrying for a long distance the rainfall the residents of São Paulo now long for. How well this pump operates, however, depends on the maintenance of the forest, the Brazilian portion of which, by 2013, had lost 763,000 square kilometers (km^2) of its original area, which is the equivalent of the three states of São Paulo. Antonio Donato Nobre, a researcher at the National Institute for Space Research (INPE), is not pointing a finger at the culprits. What matters to him is the reversal of this process and not just stopping deforestation but restoring the forest. In the report *The Future Climate of the Amazon* (released in late October, 2014), he states that the only reason not to take immediate action to reduce deforestation is ignorance of scientific knowledge. For him, the way forward is to educate the public. “Now is a good time because the taps are running dry,” he says.

In his report, drawn from the analysis of approximately 200 scientific works, he shows that every day, the Amazon Basin forest produces 20 billion metric tons of water (20 trillion liters). That amount is more than the 17 billion metric tons that the Amazon River pours into the Atlantic Ocean each day. This “vertical river” is what feeds the clouds and helps to change the direction of the winds. Nobre says that maps of the winds over the Atlantic show that, in the Southern Hemisphere and at low altitudes, the air moves northwest toward the Equator. “In the Amazon, the forest deviates from that order,” he says. “During part of the year, the moisture-laden trade winds come from the Northern Hemisphere and converge to the west/southwest, entering South America.”

This circulation pattern violates a weather paradigm that says that winds should blow from regions with colder surfaces to those with warmer surfaces. “In the Amazon, all year they go from warm, the equatorial Atlantic, to cold, the forest,” he says. A partnership with Anastasia Makarieva and Victor Gorshkov, two scientists with the Nuclear Physics Institute of Petersburg, has helped to explain the meteorological phenomena of the Amazon from a physical point of view. In an article published in the February 2014 issue of the *Journal of Hydrometeorology*, they assert, based on theoretical analyses confirmed by empirical observations, that deforestation is altering the pressure patterns and may be causing a decline in the moisture-laden winds coming from the ocean to the continent. The group analyzed data from 28 weather stations in two areas of Brazil and noted that the winds coming from the Amazon rain forest carry more water and are associated with higher rainfall rates than winds coming from deforested areas that arrive at the same station.

This phenomenon occurs, the researchers say, because of the biotic pump of moisture, a theory proposed by the Russian duo in 2007 to explain the dynamics of winds driven by forests. This idea complements the description by José Antonio Marengo (a climatologist and, at the time, an INPE researcher) of how the Amazon exports rain to the more southern regions of South America. The biotic pump theory applies an unusual physics to meteorology and postulates that the condensation of water, promoted by the transpiration of the forest, reduces the atmospheric pressure that sucks the air currents laden with water from sea to land.

The reasoning behind the influence of condensation on winds was presented in an article published in 2013 by Anastasia and Gorshkov, in partnership with Nobre and other collaborators, in *Atmospheric Chemistry and Physics*, one of the most important journals in the field. Through a series of equations, they demonstrated that the water vapor released into the atmosphere through forest transpiration generates, upon condensation, a flow capable of propelling winds over large distances. According to Nobre, the new physics of condensation they proposed generated a dispute among meteorologists, even during the review of the article. The principal equation of the work was furiously discussed on scientific blogs. These attempts to discredit the new model failed, and the work was published. Nobre can explain the controversy. “The new physics attributes to condensation a basic and central phenomenon of how the atmosphere operates, an effect contrary to what was previously believed,” he says. “Textbooks on the subject will have to be rewritten.”

To explain the scope of the problematic dialogue between theoretical physicists and meteorologists, Nobre says that physics develops its understanding of atmospheric phenomena based on the fundamental laws of nature, while meteorology does it largely based on observations of past climate patterns, whose statistical data are absorbed into mathematical models. Such models are very good at representing observations of climate fluctuations but fail when there are significant changes in the pattern.

This is now the case, when a new context—caused by deforestation, global changes in climate or other factors—is generating unexpected weather phenomena for certain regions, such as more torrential rains and more extensive droughts. Physical theory is correct where past extrapolations err; therefore, it is necessary, he says, to build new climate models that collect the physical data at the center of meteorological efforts.

The timing is now crucial because the Amazon’s climate is changing. The years 2005 and 2010 were marked by major droughts in this region. “Prior to this, the Amazon had a wet season and a wetter season, but now there is a dry season,” says Nobre. The damage to the forest caused by these droughts was not a fatal blow because the Amazon can regenerate, but the accumulated damage could gradually erode this regenerative capacity. An important effect previously noted (predicted 20 years ago by climate models) is an extended dry season, which has undermined agricultural production in parts of Mato Grosso State. The major concern is when the forest reaches a tipping point, where it can no longer produce enough rain to supply itself. Models that take into account climate and vegetation indicate that the tipping point will be reached when 40% of the original forest is lost, a number about which there is no consensus. According to Nobre’s report, 20% of the forest has been cut and 20% has been altered to the point of losing some characteristic properties.

If the biotic pump theory is correct, the effects of this tipping point are likely to be more severe than the savannization proposed by Carlos Nobre, also a climatologist and the older brother of Antonio Nobre (*see* Pesquisa FAPESP *Issue No. 167*). “If the forest loses its ability to bring moisture from the ocean, rain in the region may cease altogether,” says Antonio Nobre. Without water to sustain a savannah, desertification could occur in the Amazon. If this occurs, the scenario he envisions for Brazil’s South and Southeast could be similar to other regions at the same latitude, turning them into deserts.

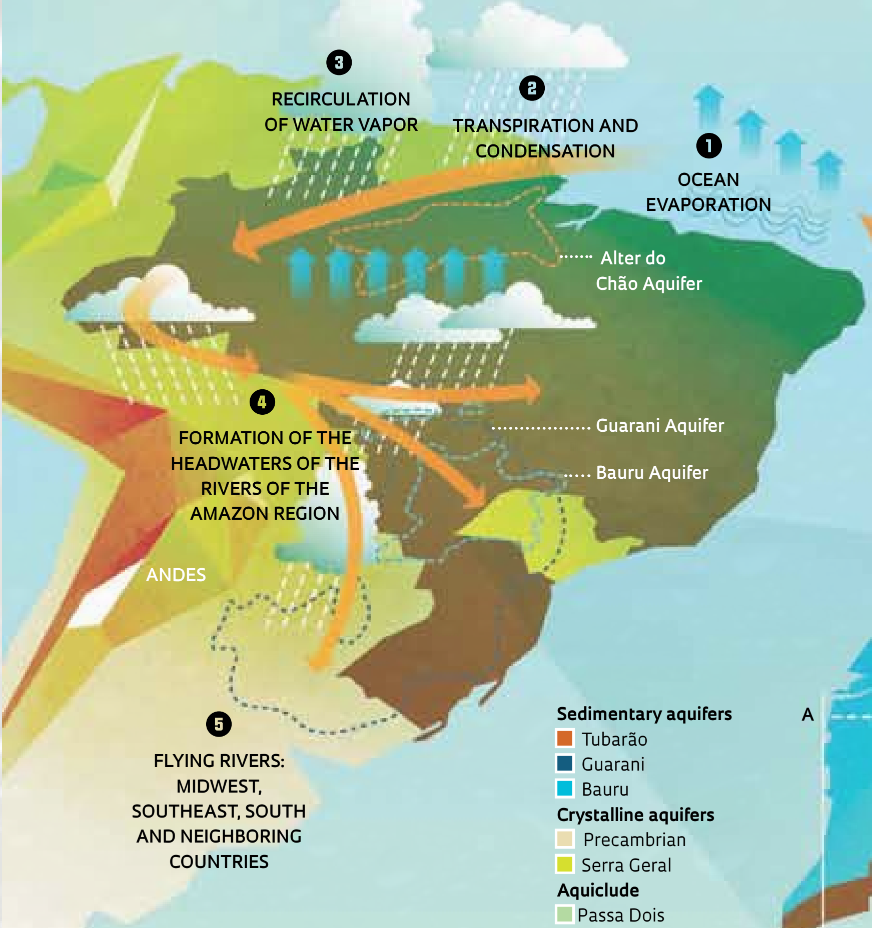
Antonio Nobre does not say too much about Sao Paulo. “My report is about the Amazon.” However, he believes that the drought in São Paulo is not isolated from what is happening in the North. In his view, it was possible to devastate much of the Atlantic Forest without experiencing a reduction in rainfall because the Amazon was able to make up for the lack of water in the local atmosphere. However, that no longer seems to occur. His report is an opportunity for him to urge that not only the Amazon rain forest but also almost all of the coastal forest area of Brazil must be immediately recovered. If for no other reason, the depletion of the dams that feed much of the São Paulo population should suffice as an argument.

The export of water from the Amazon to other regions of Brazil, especially the Southeast and the South, is a reality and occurs through the phenomenon known as flying rivers (*see* Pesquisa

INFOGRAPHIC ANA PAULA CAMPOS **ILLUSTRATION** FABIO OTUBO

Pathways to the tap

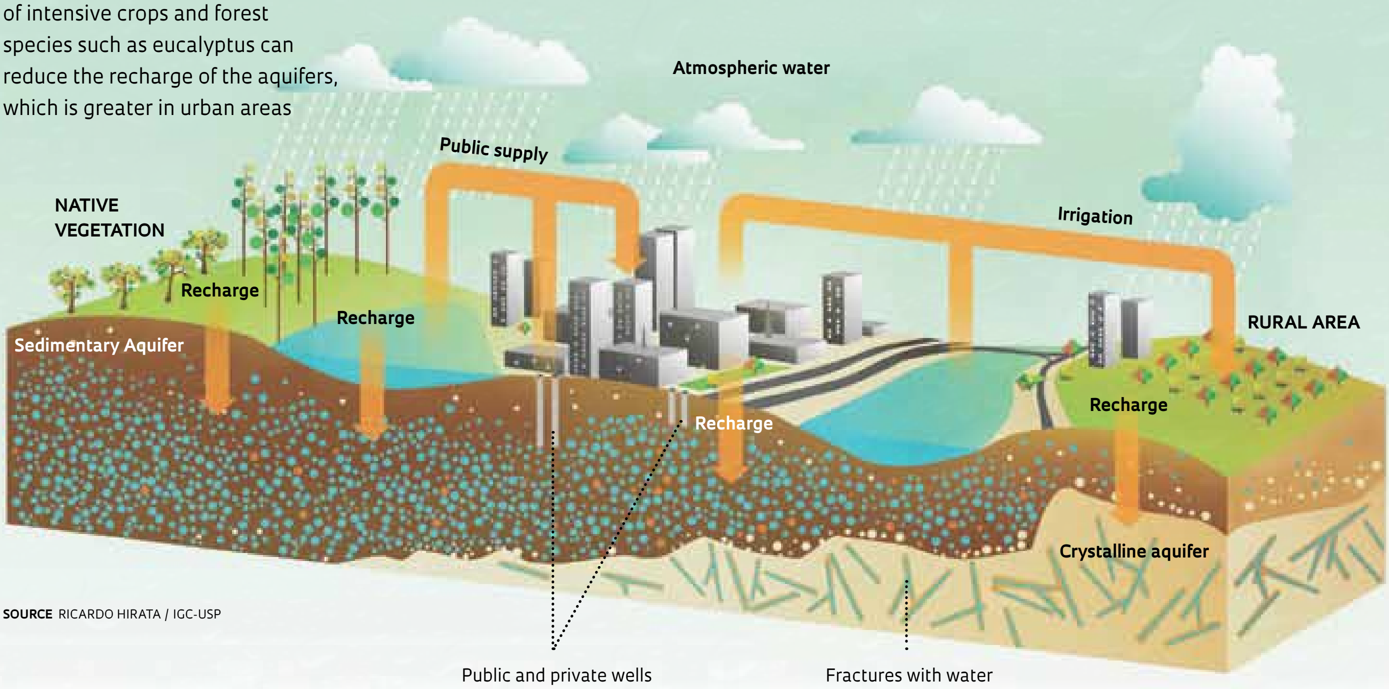
Air, surface and ground sources are added to the supply



FLYING RIVERS
The Amazon rain forest sits atop a huge amount of water, the Alter do Chão aquifer. Its vegetation absorbs moisture from the groundwater and the ocean and releases it into the atmosphere in the form of vapor, creating air currents that export rains to distant places

SÃO PAULO AQUIFERS
The overlap of underground sources in the state of São Paulo is an example of the system's complexity; the aquifers are used as the only or partial source of water in 75% of its municipalities

IN RURAL AND URBAN AREAS
The presence of native forest is essential to the health of watersheds. The planting of intensive crops and forest species such as eucalyptus can reduce the recharge of the aquifers, which is greater in urban areas



SOURCE RICARDO HIRATA / IGC-USP

GERARD MOSS / FLYING RIVERS DESIGN

Flying rivers: currents of water vapor that form over the Amazon rain forest export rains to southern Brazil

FAPESP *Issue No. 158*). One indication of this direct connection was the heavy rains in southwestern Amazonia in early 2014, which were almost double the usual volume, while São Paulo experienced a historic drought. "The rain was trapped in Rondônia, Acre and Bolivia because of atmospheric blocking, similar to an air bubble that prevented the passage of moisture. This created an atmospheric stability, inhibited the formation of rain and elevated temperatures," says Marengo, now a researcher at the National Center for Natural Disaster Monitoring and Alerts (CEMADEN). He is the co-author of a lead article by Jhan Carlo Espinoza, of the Geophysical Institute of Peru, which is slated for publication by *Environmental Research Letters* and is part of the results of the Green Ocean Amazon (GOAmazon) program that has the support of FAPESP.

However, it is impossible to say how much this relationship affects the São Paulo drought. "Calculating how much of the Southeast's rain comes from the Amazon and how much of it is brought by cold fronts coming from the South, moisture carried by sea breezes or local evaporation is still an inexact science," he says. Marengo believes that deforestation may have a long-term impact, but it is still impossible to say whether it is related to the current drought. "The Southeast may not turn into a desert," he adds, "but weather extremes may become more intense." Studies using climate models created by the Marengo group already forecast a redistribution of total rainfall, with a very heavy volume over a few days and longer droughts, which is something that has already been observed in Brazil's Southeast and South in the last 50 years.

In addition to this effect-at-a-distance on a national scale, the relationship between vegetation and water resources also occurs on a more local scale, according to Walter de Paula Lima, an agronomist and professor at the Luiz de Queiroz School of Agriculture (ESALQ) of the University of São Paulo (USP) and the scientific coordinator of the Cooperative Environmental Monitoring Program on Microbasins (PROMAB) of the Institute of Forestry Research and Studies. In his studies on the effect of forests (or their removal) on microbasins, he showed that the riparian forest bordering watercourses helps to maintain the health of small rivers. "The Cantareira system, which supplies São Paulo, consists of thousands of microbasins," he says. "Those that are more degraded do not contribute to the watershed." This assessment, however, lacks concrete experimental data. According to Lima, to discover exactly how riparian forests affect watersheds, it would be necessary to study an experimental microbasin where the properties of watercourses could be measured with and without forest protection, and absent any other factors—a virtually unattainable scenario.

A practical experience that reinforces the importance of preserving riparian forests to maintain water resources has been reported by Ricardo Ribeiro Rodrigues, an ESALQ biologist and recovery specialist of native forests. He says that 24 years ago, the water disappeared from the microbasin in Iracemápolis, a city located in São Paulo State. The city sought help from ESALQ, and Rodrigues' group implemented a soil conservation project for the microbasin and recovery of the riparian vegetation that should be there. "I was recently there and was very surprised," he says. The level of the dam is a little lower, but it has enough water to continue supplying Iracemápolis, whose population has tripled since then. "The whole region is experiencing water shortage problems but not Iracemápolis."

Forests affect water resources through their influence on rainfall and groundwater recharge

Forests affect the health of water resources through their influence on rainfall but are also important in regard to their relationship with groundwater. Edson Wendland, an engineer and professor in the Department of Hydraulics and Sanitation, São Carlos School of Engineering (EESC-USP), is studying precisely what happens to the Guarani aquifer recharge when the Cerrado is replaced with pasture and crops such as sugarcane, citrus or eucalyptus. The work is being conducted in the Ribeirão da Onça Basin, city of Brotas, São Paulo State, which has been studied since the 1980s.

Through monitoring wells and weather stations, the idea is to detail how the Guarani aquifer recharges under different land use systems before there is no more of the Cerrado's original vegetation left. "It is impossible to manage what we don't know," says Wendland about one of Brazil's most important groundwater sources. The aquifer is a porous layer of rocks infiltrated by rainwater, which is then slowly released into rivers. This time difference between supply and discharge, a result of the slow path of the water through the underground aquifer, is what ensures the continuity of rivers, which depend on this water reserve.

Wendland's group has shown, for example, that water availability decreases when the small twisted trees of the Cerrado, which have adapted to living under water stress, are replaced by eucalyptus trees, which consume a lot of water and reach cutting size within a few years. Measurements made between 2004 and 2007 show that recharge rates are closely related to the intensity of the rainfall and the size of the crop in this region where the Cerrado is virtually extinct, according to an article accepted for publication in the *Annals of the Brazilian Academy of Sciences*.

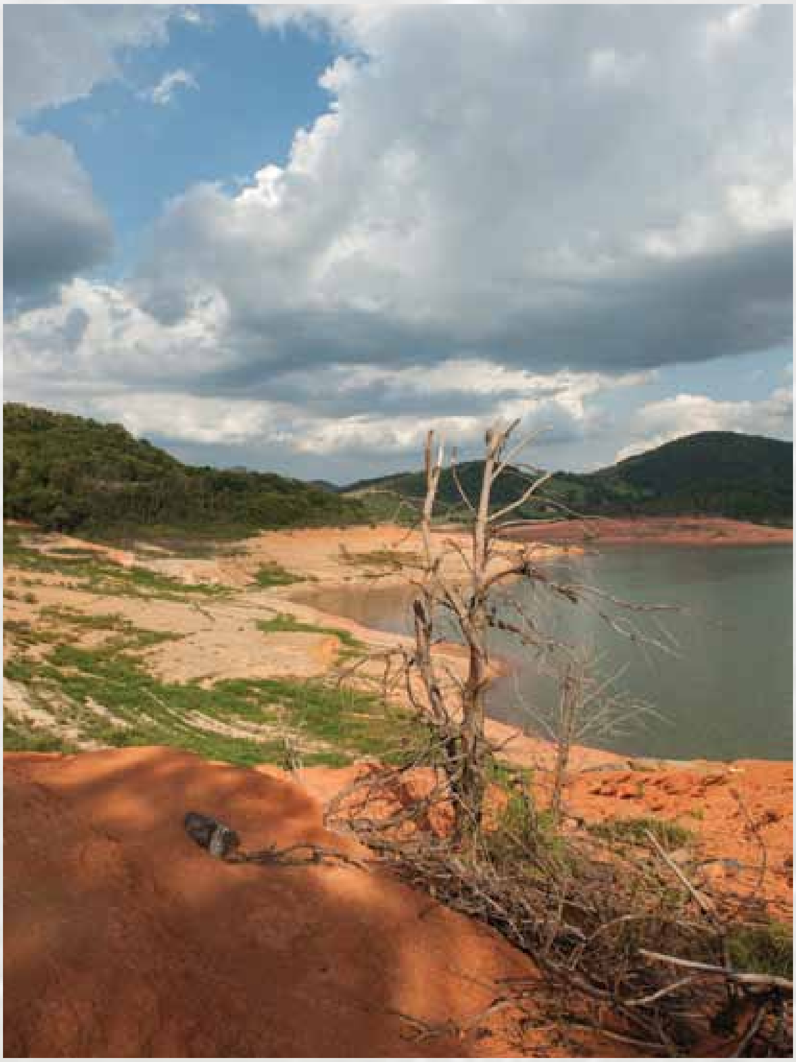
However, this does not mean that eucalyptus trees are unconditional villains. The impact of large trees depends, in part, upon the depth of the aquifer at the location where they are planted. According to Lima, trees that PROMAB has continuously monitored for a period of more than 20 years showed that the relationship between forest species and water is not constant. "Where availability is critical, a new element can dry the microbasins," he says. "However, where water and climate balance is good, the water reduction is not even felt." These findings make it clear that a zoning plan is needed to indicate where planting would be good and where the practice would be harmful—something that does not exist in Brazil.

To Wendland, the importance of understanding the relationship between the Cerrado and the aquifers is crucial, because the sources of most of Brazil's major river basins are in the domain of this biome. In addition to their importance as water resources, some of these basins—Paraná, Tocantins, Parnaíba and São Francisco—are the main providers of water for power generation in Brazil.

In just over half a century, half of the Cerrado area was cleared and given over to agricultural activities. To evaluate the effect of this change in land use on water availability, Paulo Tarso de Oliveira, a doctoral student in the São Carlos group, conducted a study using remote sensing data from the entire area of the Cerrado biome. With the sensors, it is possible to not only evaluate the changes in vegetation but also measure the rainfall and the evapotranspiration rates of plants and estimate the variation of water storage. According to an article published in the September 2014 issue of *Water Resources Research*, the data indicate a flow reduction because of more intense agricultural activities.

Deforestation and the agricultural use of soil are important, but Wendland says the biggest problem affecting aquifer recharge today is the reduction in rainfall. "The aquifer can make up for the lack of rainfall for two or three years, but after that it can no longer maintain the base flow in rivers," he says. In recent years, the rainfall of the rainy season has been below average, according to observational data. It also explains, he says, alarming phenomena, such as the depletion of the headwaters of the São Francisco River, which remained dry for about three months and only returned to a flow stage at the end of November.

The challenge of managing groundwater, representing 98% of the planet's fresh water, has other peculiarities in urban areas, where it can be a crucial resource. According to Ricardo Hirata, a geologist with the Geosciences Institute (IGc-USP), 75% of São Paulo's municipalities are supplied in whole or part by groundwater. This includes major cities of the state, especially Ribeirão Preto, where 100% of more than 600,000 residents are served. Nationwide, there are other cities completely supplied by groundwater, such as Juazeiro do Norte (Ceará State), Santarém (Pará State), and Uberaba (Minas Gerais State), according to the book *Águas subterrâneas urbanas no Brasil* [Urban Groundwater in Brazil], slated for publication by IGc and the Research Center for Groundwater (Cepas).



Surprisingly, in the cities, it is the water lost by the public supply that will stop the aquifer. "The impermeability of the soil reduces rain water penetration, but the losses offset and overcome this reduction and on balance there is greater recharge where there are cities, compared to other areas," says Hirata. "If we analyze the water from a well anywhere in São Paulo, half will be from the aquifer and half from Sabesp (water and sewage management company owned by the state of São Paulo)." He estimates that the state capital has nearly 13,000 private wells, and many of them are illegal. "There is a law to manage this resource, but it is not followed," he says.

A problem caused by the cities is groundwater contamination by nitrate due to leaks in the sewer system. As decontamination is expensive, the affected wells are abandoned. In cities where the aquifers are used for the public water supply, the solution is to mix the polluted water with water from clean wells so that the overall quality is acceptable. "In Natal (capital of Rio Grande do Norte State) there is insufficient water to mix," says Hirata. Groundwater is the source of 70% of its supply.

Another significant source of pollution comes from industry, such as the pollution caused by chlorinated solvents. Reginaldo Bertolo, an IGc geologist and director of Cepas, studies how this pollutant behaves in the aquifer below Jurubatuba, in the south São Paulo area, which has been an industrial region since the 1950s. "It is a contaminant with problematic behavior in the aquifer," he says. In this hard rock, where the water flows into fractures, the compound, which is denser than water, goes deeper and only stops when it encounters an impermeable stratum. "Chlorinated solvents are toxic and carcinogenic products." Pollution prevents the use of groundwater in a region where the demand is strong.

In collaboration with researchers at the University of Guelph in Canada, the Bertolo group is mapping these pollutants in order to understand how the chlorinated solvent compound behaves and to propose strategies to eliminate it from the aquifer. To achieve this, the next step is to use a system developed by the Canadian researchers to take rock samples and install special monitoring wells. "The equipment allows us to collect water from more than 20 different fractures in the same drilling," he says. "We're going to do a mathematical model to reproduce what happens and make some forecasts."

Bertolo says it is important to better map the groundwater and analyze its quality, because it is a resource that can supplement city water supplies. "Groundwater is a little-known resource."

In late November, the Cantareira system had water in the Paiva Castro reservoir (*right*), while the drought was evident at the Jacarei and Jaguari reservoirs

Monica Porto, an engineer at the USP Polytechnic School (Poli/USP), does not believe it is possible to greatly expand the use of these waters in the São Paulo Metropolitan Region. In her opinion, to go beyond a flow rate of approximately 10 cubic meters per second (m^3/s) extracted from thousands of existing wells would take thousands of new drillings. "However, we can not do without these 10 m^3/s; we need to take care of them."

Porto, who was a past president and is still a member of the advisory board of the Brazilian Association of Water Resources, is considering ways to ensure a secure water supply for the population. Lack of water is, in fact, among the most serious things that can happen to a city. "We are forced to work with a very low probability of failure." According to Porto, in 2009 the São Paulo state government commissioned a consulting firm to do a study on what would need to be conducted to guarantee the water supply. The study was completed in October 2013, when the state was already in the midst of the most severe water crisis in its history. Porto says it is impossible to consider Greater São Paulo in isolation because there is nowhere else to draw water from without a dispute with neighbors. Therefore, the study covers the mega-metropolis, which includes more than 130 municipalities and a population of 30 million people.

The development of the public works needed to improve water security has began, with a system to collect water from the Juquiá River in the Ribeira Valley, which should be completed by 2018. Construction of the Pedreira and Duas Pontes dams, which should supply the Campinas region, is in the environmental licensing phase. "Manaus and Campinas are the only cities in Brazil with more than one million people and no water reservoir," says Porto. Manaus does not need a reservoir, as it is situated on the banks of the Amazon River; however, Campinas, which relies on the Cantareira system, does need one. Porto, who "makes a great effort" to save water at home, says the current crisis is important for raising public awareness about the need to reduce consumption. It also highlights the importance of the set of measures that need to be reviewed on an emergency basis. "We have to learn from the pain," she says, and jokingly adds that it is better if it does not rain enough to drive away the instructive crisis. "However, if it does not rain very soon, I will stop joking: we need rain." ■

> See videos on our website: revistapesquisa.fapesp.br

Projects

1. Understanding the causes of the biases that determine the onset of the rainy season in Amazonia in climate models using GoAmazon--CHUVA [rain project] measurements (No. 13/50538-7); **Principal investigator** José Antonio Marengo Orsini (CEMADEN); **Grant mechanism** Regular Line of Research Project Award - GoAmazon; **Investment** R$57,960.00 (FAPESP).

2. Establishment of the hydrogeological conceptual model and fate and transport of chlorinated organic compounds in the fractured aquifer of Jurubatuba region, São Paulo (No. 13/10311-3); **Principal investigator** Reginaldo Antonio Bertolo (IGc-USP); **Grant Mechanism** Regular Line of Research Project Award; **Investment** R$502,715.27 (FAPESP).

Scientific articles

MAKARIEVA, A.M. *et al.* Why does air passage over forest yield more rain? Examining the coupling between rainfall, pressure and atmospheric moisture content. **Journal of Hydrometeorology**. V. 15, Nº. 1, p. 411-26. February 2014.

MAKARIEVA, A.M. *et al.* Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. **Atmospheric Chemistry and Physics**. V. 13, p. 1039-56. January 25, 2013.

ESPINOZA, J. *et al.* The extreme 2014 flood in South-western Amazon basin: The role of tropical-subtropical South Atlantic SST gradient. **Environmental Research Letters**. In press.

WENDLAND, E. *et al.* Recharge contribution to the Guarani Aquifer System estimated from the water balance method in a representative watershed. **Annals of the Brazilian Academy of Sciences**. In press.OLIVEIRA, P.T.S. *et al.* Trends in water balance components across the Brazilian Cerrado. **Water Resources Research**. V. 50, Nº. 9, p. 7100-14. September 2014.