Water Resour Manage (2010) 24:761–773
DOI 10.1007/s11269-009-9470-x

Water Resources Assessment at Piracicaba, Capivari and Jundiaí River Basins: A Dynamic Systems Approach

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Received: 10 December 2008 / Accepted: 9 June 2009 /
Published online: 25 June 2009

Abstract The Piracicaba, Capivari, and Jundiaí River Basins (RB-PCJ) are mainly located in the State of São Paulo, Brazil. Using a dynamics systems simulation model (WRM-PCJ) to assess water resources sustainability, five 50-year simulations were run. WRM-PCJ was developed as a tool to aid decision and policy makers on the RB-PCJ Watershed Committee. The model has 254 variables. The model was calibrated and validated using available information from the 80s. Falkenmark Water Stress Index went from 1,403 m^3 $person^{-1}$ $year^{-1}$ in 2004 to 734 m^3 P^{-1} $year^{-1}$ in 2054, and Xu Sustainability Index from 0.44 to 0.20. In 2004, the Keller River Basin Development Phase was Conservation, and by 2054 was Augmentation. The three criteria used to evaluate water resources showed that the watershed is at crucial water resources management turning point. The WRM-PCJ performed well, and it proved to be an excellent tool for decision and policy makers at RB-PCJ.

Keywords Water stress · Water management · Watershed · Modeling

1 Introduction

Water problems are extremely complex due to different points of view and interests, such as: (a) Rural people are direct water consumers, while urban people get water

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through suppliers; (b) Water issues are related to income; (c) Water shortages are perceive differently, according to individual consumption; (d) Water issues are quantitatively and qualitatively uneven in time and space within a basin; and (e) Water is an essential resource for life and society. Therefore, increasing interest in its conservation and correct use is developing. There are many perspectives, interests, perceptions and alternatives for use of water resources due to the diversity of people involved and their social status, occupations, income, priorities and locations.

Water resources management should be linked to environmental sustainability, which is a function of the growth of each component in the watershed. Considering that agriculture is responsible for food production and large volumes of water consumption, it is a key point in our analysis. A population's income growth implies a substantial increase in the demand for water and food as well as an increase in the contamination of bodies of water.

Then, questions arise, such as: Up to what point it is possible to maintain the growth of productive activities in diverse areas of the economy and still satisfy the growing demands of the population without harming water resources sustainability? What level of river basin development are Piracicaba, Capivari, and Jundiaí watersheds at (RB-PCJ)? Is irrigation sustainable at RB-PCJ? These are important questions to be answered by the assessment of water resources at RB-PCJ using the Water Resources Model for the Piracicaba, Capivari, and Jundiaí River Basin (WRM-PCJ). In Brazil, the RB-PCJ is part of the Water Resources Policy lead by the National Water Agency (Agência Nacional de Águas), which is responsible for implementing and articulating the connections between the management of the River Basin Committees (RBC) and taxing all of the federal water resources.

A direct relationship exists between water resources and the systemic approach because both are systemic and non-linear (Ohlsson and Turton 1999). The basic principle of any systemic study is connectivity. A system is a set of elements with connections amongst themselves and their environment. Each system is composed of subsystems that are all part of a larger system, with each one being autonomous and simultaneously open, directly interrelated and integrated with its environment (Santos 1982).

The systemic approach is used in water resources management to analyze and improve systems. The units that belong to a water resources system are part of a dynamic and complex system, where many activities and explorations coexist and interact. Each activity has inputs, such as labour, power, capital, etc., and outputs, such as agricultural goods, residues, agricultural and industrial contaminants, etc. (Costa 1993). However, water resources sustainability should be linked to the users' capacity to conserve or increase quality of life; maintaining and guaranteeing those resources for future generations, also known as adaptive capacity (Turton 1999).

The Dynamics System (DS) methodology is based on and derived from the Theory of Control developed by Forrester (1961). The fundamental principle of this methodology is that every dynamic behavior is a consequence of the system structure (POWERSIM 1996). It is characterized by changes happening along the time.

DS simulation models are real world abstract descriptions. They represent complex problems and are characterized by their dynamics, none-linearity, feedback relationships and discrepancies in time and space (Wiazowski et al. 1999). A DS model should capture only the essential factors of a real system and disregard all the other factors. The main use of the model is to communicate a point of view on specific problems. It does not try to be the reality but to be as close as possible to it and to predict its behavior (Perez Maqueo et al. 2006). The user should always be conscious of the limitations of the model he/she is using.

When focusing on a problem, there are several ways to use simulation models. The objectives that guide the WRM-PCJ construction define its structure. With this in mind, and based on other countries experiences and other watersheds' development trends, a DS simulation model was developed and run. This model intended to define an up-to-date RB-PCJ development stage and to assess water resource availability and agriculture sustainability for the next 50 years.

2 Materials and Methods

WRM-PCJ uses object-oriented DS on a STELLA 9.0 platform. The model relates environmental, physical, social and economical elements to explain the dynamic behavior of water resources that are offered and demanded and wastewater generated by using several existing consumers in RB-PCJ. The model is a tool to aid policy makers and decision makers to find different alternatives to manage water resources at RBC-PCJ.

To analyze the impact of water resource sustainability due to water offered and demanded, WRM-PCJ uses: the Sustainability Index (Xu et al. 2002), which defines the relationship between total consumption and total available water, and the Falkenmark Index (Falkenmark 1989; Falkenmark et al. 2007), which relates use-to availability (Level of exploitation) and the number of people who have to share an unit of water (water shortage).

When analyzed water resources use to available water ratio through time, river basin development phases proposed by Keller et al. (1998) were considered. These development phases characterize the development, or management, stage at which the watershed is. This information is important to establish water demand trends, which is valuable information for decision and policy makers to take adequate measures to guarantee water resources sustainability.

2.1 Consumer Water Demand

Water demand was defined based on in situ studies of water consumption habits in the area. All information was collected and presented in several Water Resources State Plans, many secondary information sources linked to agencies that support productive sectors, and by the water resources administration (PERH 2004, 2005; SIRGH 2007; SABESP 2007; DAEE 2007; IEA 2007; UNICA 2007; IBGE 2007; IPEA 2007; INPE 2007; INMET 2007).

To be effective and precise when modeling irrigated agriculture and animal breeding, it is necessary to have a detailed knowledge of water consumption and wastewater generation. To do this, it is necessary to conduct a water user census, with detailed information on water habits. The lack of information on these topics created some uncertainties during the simulations.

Regarding ecological flow, several methodologies were considered to define a value for the simulations. It was decided to use the smallest value that could be computed. This consideration was based on the fact that the ecological flow value should be a decision taken at the RBC-PCJ; but the concept of ecological flow is introduced for the first time at the RB-PCJ water demand balance. A French method for existent water systems uses a value equal to 1/40 of the average daily flow (Souchon and Keith 2001). According to PERH (2005), the average daily flow for RB-PCJ is 64 $m^3\ s^{-1}$. Therefore, the ecological flow used during the WRM-PCJ runs was 1.6 $m^3\ s^{-1}$ for four scenarios, and 19.6 $m^3\ s^{-1}$, for a sensibility analysis, for one scenario representing 30% of the average daily flow, a more usual value used for ecological flow (Falkenmark et al. 2007).

2.2 Study Area Characterization

Three watersheds form the RB-PCJ system, known as Water Resources Management Unit 5 (UGRHI-5), were studied. This unit includes 64 municipal districts, 60 belonging to the State of São Paulo and four belonging to the State of Minas Gerais (PERH 2005). RB-PCJ has a total area of 15,414 km^2.

The three rivers (Fig. 1) flow toward the Tietê River and belong to Rio Tietê River Basin. The estimated population at UGRHI-5 in 2004 was 4,434,937 urban inhabitants and 223,998 rural inhabitants (PERH 2005). The main economic activities are: industry, agriculture, agro industry, mining, recreation and landscaping, and commerce and services. By 2005, the RB-PCJ was responsible for the production of 5.8% of Brazil's GNP.

2.3 Water Resource Systems Structures

Figure 2 is the causal diagram of the water resources system structure that was modeled to analysis the water resources sustainability at the RB-PCJ study area.

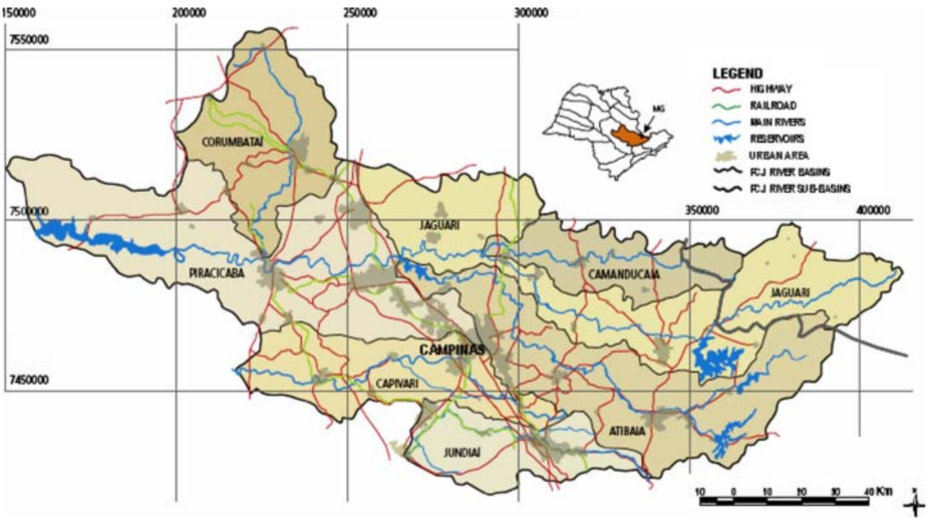

Fig. 1 Piracicaba, Capivari and Jundiaí River Basins (source: PERH 2005)

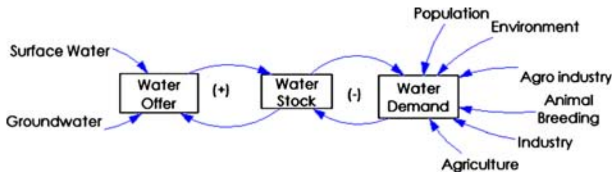

Fig. 2 Causal diagram for the Piracicaba, Capivari and Jundiaí water resources system

The Water Offer variables are: surface water and groundwater; both variables guarantee the Water Stock from where water is drawn by consumers. Water Demand is the sum of the water demands from the population, environment, agro industry, animal breeding, industry, and agriculture.

2.4 Piracicaba, Capivari and Jundiaí River Basins Water Resources Model (WRM-PCJ)

WRM-PCJ is an explicit dynamic simulation model developed to simulate the RB-PCJ water resource system. The WRM-PCJ has 254 variables in 11 sectors; these sectors can be grouped as: demand, offer, and specific computations. The demand sectors are: Agriculture, Animal Breeding, Agro-industry, Environment, Population, and Industry. The Offer Sector has surface water and groundwater to offer as a product of annual precipitation, a variable that can change annually. The Computation Sector includes: Wastewater Returned Volume, Total Water Demand, Water Allocation Incomes, and Equivalent Population.

The water balance equation (1), at RB-PCJ expressed as a finite-difference equation in WRM-PCJ, is:

$$\begin{aligned}\text{BalanHidric}(t) = {} & \text{BalanHidric}(t - dt) \\ & + \left(\text{SUPPLY} - \text{Vol\_Water\_exit\_BHPCJ-Total Consumption PCJ}\right) \\ & * dt \end{aligned} \tag{1}$$

where BalanHidric(t) is the Water balance for year t (m^3 $year^{-1}$); SUPPLY is the Water Offer for year t (m^3 $year^{-1}$); Vol_Water_exit_BHPCJ is the Water Volume that runs off Piracicaba, Capivari and Jundiaí Watershed Basin (m^3 $year^{-1}$); and, Total Consumption PCJ is the Total Water Demand by consumers at Piracicaba, Capivari and Jundiaí Watershed Basin (m^3 $year^{-1}$).

The water offer (2), total consumption (3), use to availability (4), water per capita available (5), water shortage (6) and sustainability index (7) equations in WRM-PCJ are:

$$\text{OFFERT} = \text{Total\_Runoff\_Vol} + \text{Total\_Infilt\_Vol} \tag{2}$$

$$\begin{aligned}\text{Total\_Consumption\_PCJ} = {} & \text{VTRAG} + \text{VTRAI} + \text{VTRamb} \\ & + \text{VTRInd} + \text{VTRpop} + \text{VTRPEC} \\ & + (\text{Demanda\_RMSP} * 86400 * 365)\end{aligned} \tag{3}$$

$$\text{Use2Av} = 100 - \left(1 - \left(\text{Total\_Consumption\_PCJ} \big/ (\text{Runoff\_Vol} + \text{Infilt\_Vol})\right)\right) * 100 \quad (4)$$

$$\text{WatPerCapAva} = (\text{Runoff\_Vol} + \text{Infilt\_Vol}) \big/ \left(\text{Rural\_Pop} + \text{Urban\_Pop}\right) \quad (5)$$

$$\text{Water shortage} = 1 * 10^{-6} \big/ \text{WatPerCapAva} \quad (6)$$

$$\text{Sust\_Index} = \text{WaterBalan} \big/ \text{OFFERT} \quad (7)$$

where OFFERT is total water volume available at RB-PCJ (m^3 $year^{-1}$); Total_Runoff_Vol is total runoff water volume produce by precipitation (m^3 $year^{-1}$); Total_Infilt_Vol is total water volume that infiltrates (m^3 $year^{-1}$); VTRAG is total water volume consumed by agriculture (m^3 $year^{-1}$); VTRAI is total water volume consumed by agroindustry (m^3 $year^{-1}$); VTRamb is total water volume committed to environmental flow (m^3 $year^{-1}$); VTRInd is total water volume consumed by industry (m^3 $year^{-1}$); VTRpop is total water volume consumed by urban and rural population (m^3 $year^{-1}$); VTPEC is total water volume consumed by animal breeding (m^3 $year^{-1}$); Demanda_RMSP is total water volume diverted to São Paulo Metropolitan Area, usually is 31 m^3 s^{-1} (m^3 $year^{-1}$); Use2Av is a ratio between total water consumption and total water volume available, also known as water use or as use-to-availability (%); WatPerCapAva is a ratio between total water volume available and total population living at RB-PCJ (m^3 $person^{-1}$ $year^{-1}$); Water shortage is the ration between a hydrological unit (10^6 m^3) and water per capita available; Sust_Index is the ratio between water balance and water offer (unitless); WaterBalan is OFFER − Total_Consumption_PCJ.

Figure 3 represents the water resources offer structure linked to the Water Offer Section at the study area as proposed in WRM-PCJ.

Here, the variable water offer is SUPPLY (10^6 m^3 $year^{-1}$ = Mm^3 $year^{-1}$), and it represents precipitation volumes that became runoff volume (Vol Runoff Tot) or percolated and infiltrated volume annually (VolInfTot). Additionally, all return waters (VolAReturn) are also considered to be water offer. All these volumes are in Mm^3 $year^{-1}$. The use-to-availability (Use2Av) is also known as Water Resources Vulnerability Index by Raskin et al. (1997), and it is used in the graphic proposed by Falkenmark et al. (2007) as the *y*-axis (Fig. 5).

2.5 Model Validation and Calibration

Model validation has to consider model's internal logic and structure (Ruth and Hannon 1994). To study the real behavior of a system it is necessary that the model reproduce system's behavior (Forrester 1961; ITHINK ANALYST 1997; Grcic and Munitic 2005; Sterman 2005). Simulation model validation is judged by its usefulness and convenience (Forrester 1980). Simulation models validation is the demonstration that its formal conceptions are correct; in other words, that the code and mathematics are mechanically correct. The calibration is the evaluation and adjustment of model's parameters and constants to fit real initial data and simulated results (Rykiel 1996).

For the purpose of parameter estimation, the calibration period from 1980 through 2020 is showed in Fig. 4. This figure shows predicted population by RELATORIO 0 (1999) and by WRM-PCJ. The population predicted by the model WRM-PCJ when

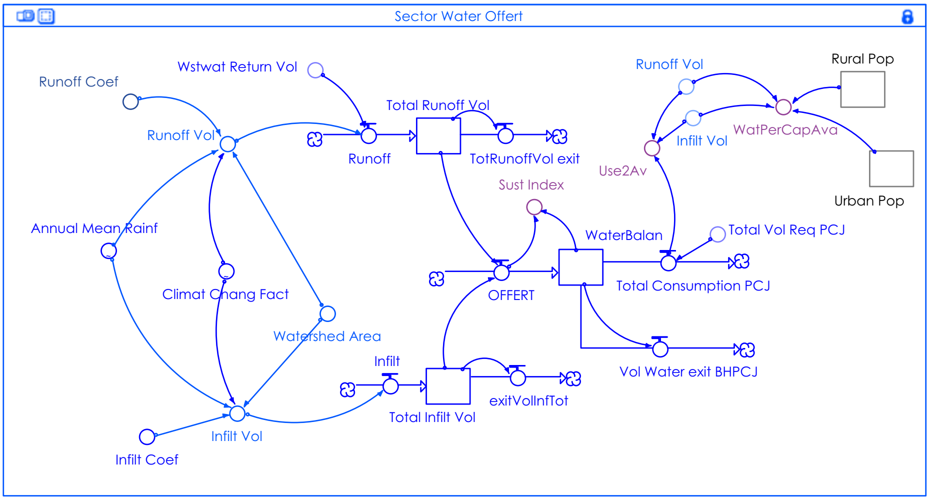

Fig. 3 Water offer sector represented by the Piracicaba, Capivari and Jundiaí River Basins Water Resources Model (WRM-PCJ) (Sánchez-Román et al. 2008)

compared with the one computed in RELATORIO 0 has a difference of 0.9%, which are nearly same. Similarly, domestic water demands for the same period are not quite different since follow population trend. Obviously, industrial sector development and the progress of the economy throughout river basins will increase gradually the percentage of water demand for industrial and domestic use, at the same time as demand for agriculture water will decrease.

Due to comparing real and computed data from the 80s to 2020 at RB-PCJ, the simulation model proposed here was validated, calibrated and evaluated. The model is suitable to characterize the internal relationships at the hydraulic system at Piracicaba, Capivari and Jundiaí river basins.

Fig. 4 Population forecast from 1980 through 2020

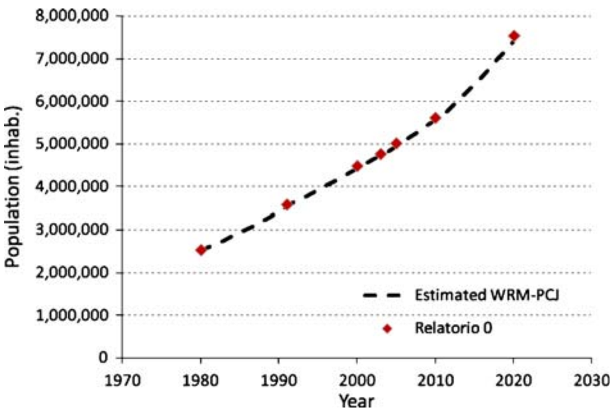

Table 1 Parameters used to create the five simulation scenarios

Parameter	Unit	Scenario				
		1	2	3	4	5
Time step	Year	1	1	1	1	1
Time frame	Year	50	50	50	50	50
Precipitation	mm year^{-1}	1,460	1,314	1,168	1,460	1,460
Irrigated area						
At 2004	ha	26,468	26,468	26,468	26,468	26,468
At 2054	ha	57,571	57,571	57,571	42,914	57,571
Growing rates						
Population	%	1.4	1.4	1.4	1.4	1.4
Manufacturing industry	%	1.5	1.5	1.5	1.5	1.5
Food and beverages industry	%	1.5	1.5	1.5	1.5	1.5
Power generation industry	%	1.5	1.5	1.5	1.5	1.5
Cellulose and paper industry	%	1.5	1.5	1.5	1.5	1.5
Sugar and alcohol industry	%	1.5	1.5	1.5	1.5	1.5
Environmental flow	m^3 s^{-1}	1.6	1.6	1.6	1.6	19.2
Flow diverted to Sao Paulo metropolitan area	m^3 s^{-1}	31	31	31	31	31

2.6 Simulation Stage: Application of the Dynamic Simulation Model

Five runs within a 50-year time frame were performed. Scenario 1, Business as Usual—BaU—water consumption and wastewater generation rates of existent consumers were maintain with no changes, using a time step of 1 year, and precipitation equal to the mean value, 1,460 mm year^{-1} (IRRIGART 2004), throughout the simulation. Scenario 2 considers a 10% reduction in precipitation due to climatic changes (CC), without variations in all other variables. Scenario 3 considers a 20% reduction in precipitation due to CC, without variations in all other variables. Scenario 4 considers the total irrigated area to stop growing in year 2020, without variations in all other variables. Scenario 5 considers the conditions set in scenario 1 and an ecological flow equal to 19.2 m^3 s^{-1} (Table 1).

3 Results and Discussion

It was observed from computed values that, for the 50-year simulation period, for the BaU scenario in RB-PCJ, an increment of approximately 76% of the total water demand in the study area should be expected. Additionally, for the BaU scenario, in 2004, total consumption represented around 74% of total available water volume without considering reused waters; by 2007, it goes up to approximately 82%, and, by 2024, it is expected that RB-PCJ will become a closed basin for two years (Fig. 5). Consumption changes foreseen by PERH (2004) produce changes in water demand conditions, for about 6 years in the basin; but these do not prevent the permanent closing of the basin in any scenario. Therefore, to supply new consumers reuse water will become the available water source.

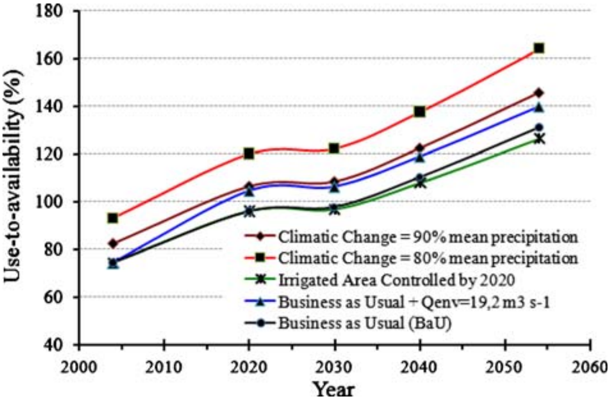

Fig. 5 Use-to-availability for Piracicaba, Capivari and Jundiaí River Basins estimated using the Piracicaba, Capivari and Jundiaí River Basins Water Resources Model (WRM-PCJ) for a 50-year time frame simulation with five scenarios

Wastewater reuse will increase the water offer, but the necessary water volume to guarantee water dilution and the sustainability of the water bodies' will be under stress since more wastewater reuse will become a water source for human activities. Without any doubt, this situation will increase water treatment price, and alternative measures to solve this situation are a must. New wastewater treatment plants should be built since it is expected that the total load will increase up to approximately 93% by 2054, in the BaU scenario.

For the BaU scenario and 50-year simulation timeframe, the water demands increase up to 24% by 2030, compared to 2004 demands. Approximately 31% of the available water volume will have its origin in wastewater reuse, and around 98% of all available water resources will be used. The total contamination load by 2030 was estimated to have increased up to approximately 39%. By 2054, the conditions will be more stressful, considering that water demand will have increased up to around 76%, as compared with the value in 2004, when approximately 39% of the available water volume will have its origin in wastewater reuse. The total demand for water resources will have risen to around 131% of the available volume. Meanwhile, the contamination load will have increased to up to approximately 91%, compared with 2004.

In Fig. 6, the 2004 Falkenmark Index for BaU scenario started at 1,403 m^3 $inhabitant^{-1}$ $year^{-1}$ (713 inhab Mm^{-3} $year^{-1}$) in RB-PCJ; by 2030 it will be 1,008 m^3 $inhab^{-1}$ $year^{-1}$ (992 inhab Mm^{-3} $year^{-1}$); and by 2054 it goes up to 734 m^3 $inhab^{-1}$ $year^{-1}$ (1,363 inhab Mm^{-3} $year^{-1}$). Water stress exists when the value is between 1,000 to 1,600 m^3 $inhab^{-1}$ $year^{-1}$, and chronic water shortage occurs when the available water volume is between 500 and 1,000 m^3 $inhab^{-1}$ $year^{-1}$. For values less than 500 m^3 $inhab^{-1}$ $year^{-1}$, the water resources are beyond the barrier of management capacity (Falkenmark 1989). The other four scenarios studied also showed that RB-PCJ will be in a chronic water shortage situation.

Also, in Fig. 6, when the basin development was analyzed using Keller et al. (1998), by 2007, BH-PCH is at Phase II, stage 1: Conservation Phase. In other words, this is the stage where policies to reduce the water demand and to increase the efficiency of water use should be taken. For the BaU scenario, by 2008, RB-PCJ will be entering Phase II, stage 2; which the final stage of this phase. By 2016, RB-PCJ will be at the initial stage of Phase III: Augmentation Phase. This is the final basin development

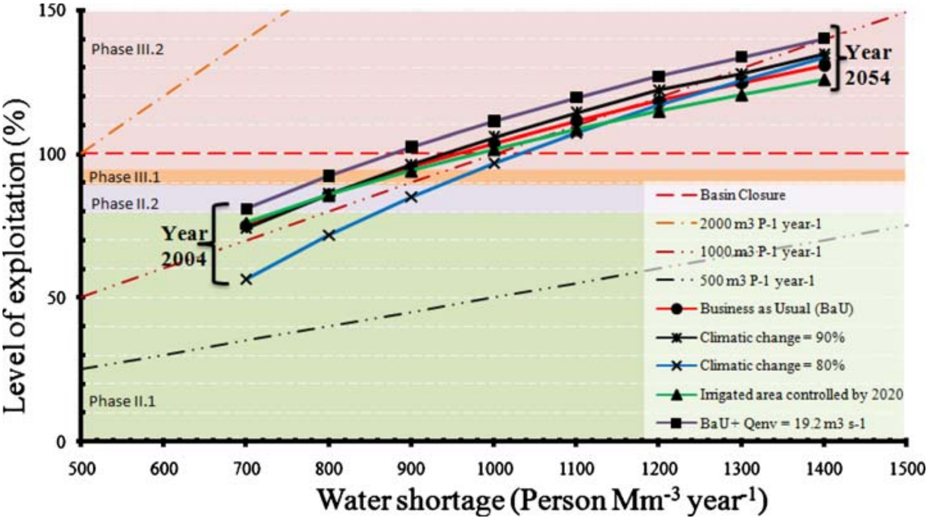

Fig. 6 Relationship between Total Water Demand and Water Availability, vertical axis, and Population Density per Unit of Flow, horizontal scale, for Piracicaba, Capivari and Jundiaí River Basins estimated using the Piracicaba, Capivari and Jundiaí River Basins Water Resources Model; for a 50-year time frame simulation with five scenarios studied (Adapted by the authors from: Falkenmark et al. 2007; and Keller et al. 1998)

phase. It is the phase where water resources have to come from water transfers or by desalting water. The other scenario predictions are also not very encouraging.

Figure 7 shows the Sustainability Index (SI) as proposed by Xu et al. (2002) and estimated using WRM-PCJ. For the BaU scenario, the SI is 0.44 by 2004. It goes down to 0.33 by 2030, and to 0.20 by 2054. The WRM-PCJ considers the reuse of wastewater as part of the available water, a contrast to the result presented by the relation use-to-availability at the y-axis in Fig. 5. If the SI value is greater than 0.2, then the water offer is under low or no stress; if the SI value is smaller than 0.2, then

Fig. 7 Sustainability Index, proposed by Xu et al. (2002), for Piracicaba, Capivari and Jundiaí River Basins estimated using the Piracicaba, Capivari and Jundiaí River Basins Water Resources Model (WRM-PCJ)

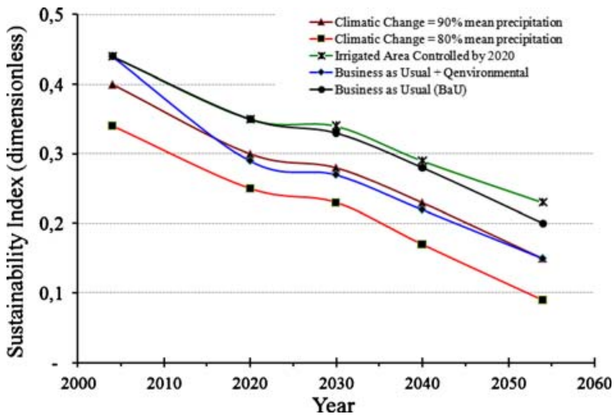

Table 2 Results of water use indexes from the five scenarios simulated using Piracicaba, Capivari and Jundiaí River Basins Water Resources Model (WRM-PCJ)

Scenario	Index	2004	2010	2020	2030	2040	2054
	WU	74.41	83.95	96.04	97.80	110.37	131.29
1	SI	0.44	0.40	0.35	0.33	0.28	0.20
	FI	1,403	1,302	1,147	1,008	884	734
	WU	82.68	93.28	106.71	108.67	122.64	145.88
2	SI	0.40	0.36	0.30	0.28	0.23	0.15
	FI	1,263	1,172	1,032	907	795	660
	WU	93.02	104.94	120.05	122.26	137.97	164.11
3	SI	0.34	0.30	0.25	0.23	0.17	0.09
	FI	1,123	1,042	917	806	707	587
	WU	74.41	83.95	96.04	96.70	107.8	126.27
4	SI	0.44	0.40	0.35	0.34	0.29	0.23
	FI	1,403	1,302	1,147	1,008	884	734
	WU	74.41	92.44	104.53	106.29	118.86	139.78
5	SI	0.44	0.34	0.29	0.27	0.22	0.15
	FI	1,403	1,302	1,147	1,008	884	734

WU Water Use (%), *SI* Sustainability Index (dimensionless), *FI* Falkenmark Index (m^3 hab^{-1} $year^{-1}$)

the water resources are vulnerable. SI values equal to zero indicate that the water offer is unsustainable.

The different methods to assess water resources and basin development at RB-PCJ showed that appropriate and urgent decisions should be taken to stop the deterioration of available water resources. By 2030 the RB-PCJ water resources situation will be extremely demanding and stressful, as the estimated coefficients showed. Additionally, by 2054, the situation will be very close to unsustainable (Table 2). Therefore, it is necessary to immediately take appropriate steps to develop a water resources management policy to avoid ecological chaos in RB-PCJ.

4 Conclusions

It can be concluded:

1. The RB-PCJ is at phase II.1 according to Keller et al. (1998) characterization of watershed development;
2. Since the lion's share is in the urban areas, it is necessary to establish a new policies to improve water saving practices by the population;
3. The model WRM-PCJ showed to be an excellent water resources management tool to be used by the watershed committee members, and it should be consider as one of its current water management decision tools and its use promoted among all committee members.

Acknowledgements The authors thank the Brazilian National Council of Scientific and Technological Development (CNPq—Processo 151864/2007-1), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP—Processo 2006/60954-4) and the National Institute of Science and Technology in Irrigation Engineering (INCTEI) for financial support.

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