JOURNAL OF ENVIRONMENTAL MANAGEMENT & SUSTAINABILITY

REVISTA DE GESTÃO AMBIENTAL E SUSTENTABILIDADE – GeAS

Received: 23 Apr. 2021 **- Approved:** 29 Sept. 2021
Evaluation Process: Double Blind Review
https://doi.org/10.5585/geas.v10i1.19876
e-ISSN: 2316-9834

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Decision support system applied to water resources management: PCJ Basins case study

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Cite as
American Psychological Association (APA)

Lopes, M. S., Tercini, J. R. B., Santi, A. D., Pedrozo, D. B., Bonnecarrère, J. I. G., Gonzalez, V. A. R., & Léo, E. C. (2021). Decision support system applied to water resources management: PCJ Basins case study. *Rev. Gest. Ambient. e Sust. - GeAS.*, *10*(1), 1-27, e19876. https://doi.org/10.5585/geas.v10i1.19876.

Abstract

Objective: Presenting the particularities of the PCJ Basin Decision Support System (SSD PCJ), highlighting its contributions to the management and planning of water resources.
Methodology: Case study based on the application of the SSD PCJ to the management actions of the PCJ Basins.
Relevance: Technological advancement implied an increase in data on water resources, requiring more time and effort to be manipulated and analyzed. Thus, investments in databases and systems that transform data into useful information are necessary, so that they can be easily accessed by users in their water resources management and planning processes. Thus, the experiences of the application of the SSD PCJ to the management of the PCJ Basins were discussed and can be replicated in other hydrographic regions.
Results: The discussions indicate that the SSD PCJ has characteristics that enhance its application to the management and planning of water resources, with public disclosure of both historical and real time data, allowing users to compare different periods and monitoring points, as well as integrated quality and quantity analyses.
Contributions: The application of the SSD PCJ has been shown to be effective in monitoring the occurrence of rain and the water bodies situation, enabling in real time the identification of risk situations and the issuance of alerts to minimize adverse impacts, besides assessing compliance with regulatory standards, feeding simulation models, and supporting analyses of water availability and quality.

Keywords: Decision support system. Information system. Water resources planning. Water resources management. PCJ Basins.

Sistema de suporte a decisões aplicado ao gerenciamento de recursos hídricos: estudo de caso Bacias PCJ

Resumo

Objetivo: Apresentar as particularidades do Sistema de Suporte a Decisões das Bacias PCJ (SSD PCJ), destacando suas contribuições à gestão e ao planejamento de recursos hídricos.

Metodologia: Estudo de caso baseado na aplicação do SSD PCJ nas ações de gerenciamento das Bacias PCJ.
Relevância: O avanço tecnológico implicou no aumento da disponibilidade de dados sobre os recursos hídricos, demandando maior tempo e esforço para serem manipulados e analisados. Dessa forma, são necessários investimentos em bases de dados e sistemas que os transformem em informações úteis, para que possam ser facilmente acessadas pelos usuários em seus processos de gestão e planejamento dos recursos hídricos. Assim, foram discutidas as experiências da aplicação do SSD PCJ no gerenciamento das Bacias PCJ, que podem ser replicadas nas demais regiões hidrográficas.
Resultados: As análises indicam que o SSD PCJ possui características que potencializam a sua aplicação na gestão e planejamento de recursos hídricos, com a divulgação pública de dados históricos e em tempo real, possibilitando que os usuários façam comparações entre diferentes períodos e pontos de monitoramento, e análises quali-quantitativas integradas.
Contribuições: A aplicação do SSD PCJ tem-se mostrado efetiva para acompanhar em tempo real a ocorrência de chuva e a situação dos corpos d’água, possibilitando a identificação de situações de risco e a emissão de alertas para minimizar impactos adversos. Ademais, serve para avaliar o cumprimento de normas regulamentadoras, alimentar modelos de simulação e subsidiar análises de disponibilidade hídrica e enquadramento dos recursos hídricos.

Palavras-chave: Sistema de suporte a decisões. Sistema de informações. Planejamento de recursos hídricos. Gestão de recursos hídricos. Bacias PCJ.

Sistema de soporte a decisiones aplicado a la gestión de recursos hídricos: caso de estudio de las Cuencas PCJ

Resumen

Objetivo: Mostrar las particularidades del Sistema de Soporte a Decisiones de las Cuencas PCJ (SSD PCJ), destacando sus contribuciones a la gestión y al planeamiento de recursos hídricos.
Metodología: Caso de estudio basado en la aplicación del SSD PCJ en las acciones de gestión de las Cuencas PCJ.
Relevancia: Los avances tecnológicos generaron un aumento en la cantidad de datos de recursos hídricos disponibles, incrementando el tiempo y esfuerzo necesarios para analizarlos y manipularlos. Así, se hace necesario invertir en sistemas que transformen los datos en informaciones útiles, para que puedan ser consumidos por los usuarios en sus procesos de gestión y planeación. Con este fin, se analizó la aplicación del SSD PCJ en la gestión de las Cuencas PCJ, ya que estos procesos pueden ser replicados en otras regiones hidrográficas.
Resultados: El estudio mostró que el SSD PCJ tiene características que potencian su aplicación en la gestión y la planeación de los recursos hídricos, con divulgación pública de datos históricos y en tiempo real, dando la posibilidad a los usuarios para hacer comparaciones entre diferentes periodos y estaciones de monitoreo, así como para realizar análisis cuali-cuantitativos.
Contribuciones: El estudio mostró que el uso del SSD PCJ fue efectivo a la hora de acompañar, en tiempo real, los eventos de lluvia y el estado de los cuerpos hídricos, permitiendo así identificar situaciones de riesgo y lanzar alertas tempranas para disminuir los impactos nocivos de dichas situaciones. También contribuyó en la auditoria de las normas y regulaciones, alimentando los modelos de simulación con parámetros de entrada y dando soporte para el análisis de disponibilidad y estado medioambiental de los recursos hídricos.

Palabras clave: Sistemas de soporte a decisiones. Sistemas de información. Planeación en recursos hídricos. Gestión de recursos hídricos. Cuencas PCJ.

Introduction

Water is an important natural resource that supports life and a productive, reliable, and equitable ecosystem and society (Gain, Giupponi & Wada, 2016). However, the economic development, overuse of water resources and water deterioration and pollution, increase risks (Quesada-Montano, Westerberg, Fuentes-Andino, Hidalgo & Halldin, 2018). Beside these issues, there are the uncertainties of global warming, which caused an overall decline of water availability in all continents in the last century (Sordo-Ward, Granados, Martín-Carrasco & Garrote, 2016).

In a global context, Brazil has a large water supply. However, regional reviews evidence that the relations between supply and demand are not uniform, mainly in metropolitan regions, such as São Paulo (MRSP) and Campinas (MRC), with around 21.5 and 3.2 million inhabitants, respectively. Both metropolitan regions are in water basins whose contributing areas have less availability than the necessary to supply the population demand, which can generate water supply instability (Braga & Kelman, 2016). Therefore, the existence of regions that have a high pressure on water resources – considering qualitative and quantitative aspects – shows an urgency to evaluate and to predict the water resources trends and evolutions. Also urgent is formulating public policies to deal with severe water crisis.

Water resources management thus requires actions of different types, including political and legislative governance, management, technological innovation, and behavior change (Gössling, 2015). Therefore, the water management process includes technical, political, legislative, and organizational aspects (Costanza et al., 2017). The technical aspects include management of water supply and demand (Ghasemi, Saghafian & Golian, 2017; Ghashghaie, Marofi & Marofi, 2014), water allocation (Karamouz, Kerachian & Zahraie, 2004), goals of water safety policies (Bolognesi & Kluser, 2018; Dadson et al., 2017) and decision support (Pallotino, Sechi & Zuddas, 2005).

Water resources monitoring is therefore important to provide data about water basins situation, considering aspects related to water availability and quality. Monitoring this information enables to detect space-time possible changes in the water bodies parameters. Water resources monitoring also helps diagnose and evaluate aquatic ecosystems and support decisions about water management.

Although water resources monitoring has several purposes, its main goals are: i) monitoring the water quality and availability changes; ii) analyzing variable trends and elaborating behavioral predictions; iii) warning about unexpected adverse impacts or trends changes previously observed; iv) detecting quality standards violation or operating rules prescribed by law; v) providing immediate information when an indicator shows critical values; vi) recording impacts resulting from such an action; vii) evaluating the effectiveness of actions held in a basin; viii) providing information enabling an assessment of correctives measures; iv) developing management tools; and x) providing resources for decision-making (Longo Júnior, 2011; Agência Nacional de Águas e Saneamento Básico [ANA], n.d.).

Considering that continuous monitoring generates a huge amount of data about the water basin, it is evident that water resources management requires a systematically organized database and computational tools that enable quick access to updated information (Santi, Lopes, Pedrozo, Léo & Barufaldi, 2020; Porto & Porto, 2008).

Therefore, the first step to implement water policies is providing data and information access about current and historical situation of water bodies and their uses (IOWater, 2013). Thus, the Water Resources Information Systems (WRIS) stand out as important management tools and must follow three basic principles: decentralization of achievement and production of data and information; unified system coordination; and guarantee of data and information access for society (Lei nº 9433, 1997).

Overall, these systems aim to gather, consist and disseminate data and information about water resources quality and availability; permanently update information about water availability and demand; provide resources to produce Water Resources Plans (Lei nº 9.433,1997). In addition, the systems intend to collect, select, and process the data to support decision-making; optimize and qualify decision-making; regularly provide information for all management levels; and democratize access to information (ANA, 2016, p. 28).

This shows that the WRIS are the heart of water resources management because the main goal of the process is making effective decisions to ensure the required availability and quality for water uses. Therefore, Porto and Porto (2008) highlighted that decision-making cannot occur without structured and updated database, being essential to invest in Decision Support System (DSS), responsible for elevating the qualification of decision-making processes.

Due to the relevant contributions of DSSs to the water resources management process, the PCJ Basins Decision Support System (SSD PCJ, an acronym in Portuguese) was developed in Piracicaba, Capivari and Jundiaí Water Basins (PCJ Basins) – case study in this paper – to support the complex decision-making process in the region. In this overview, focusing on sharing experiences, this paper presents the SSD PCJ features, highlighting the contribution to support the water resources management and planning in the PCJ Basins.

The role of DSSs in water resources management

DSSs are a knowledge resource that can facilitate decision making or achieve specific goals, integrating information about water and intervening factors into management (Moran, Saracino, Sugg, Thompson & Martinez, 2020). With more integrated approaches, they help to define sustainable policies (considering environmental, social and economic factors) and provide greater input to support both water resource planning (e.g., investments) and real time system operations (e.g. flood management) (Lima, 2007; INBO & UNESCO, 2018).

The content of these systems is complex, covering several aspects, which depend above all on their main objective; in the case of water systems, it involves total water resources and water consumption (Bagstad, Semmens, Waage & Winthrop, 2013; Moran et al., 2020; Walker, Beck, Hall, Dawson & Heidrich, 2014). Although Denzer (2005) corroborates the complexity of DSS, the author cites characteristics inherent to these systems: i) complex data in time and space, often incomplete and out of scale for the intended use; ii) complex algorithms resulting in tools linked to databases, real time monitoring systems, Geographic Information Systems (GIS), etc.; iii) problems with data control, caused by the diversity of formats and difficulties in integrating methodologies; and iv) need to unify different tools and methodologies into a single solution for the end user. In addition, Lima (2007) highlights that the systems must be made available in an online interface, with their input data and results, to provide transparency to the user.

Regarding the DSS structure, they generally consist of three interrelated modules: database, mathematical models and dialog interface. The database is responsible for storing data and information; the model base is composed of the mathematical models to be used in simulations and in the transformation of data into information; and the dialog module enables user-system interaction.

Russell, Vaughan, Clark, Rodriguez and Darling (2001) show that the technology involved makes it possible for DSS to be able to provide simple and powerful tools to import, organize, manipulate, and export large amounts of data, and that GIS play an important role by storing data spatially. The database must feed the models, allowing users to build and analyze alternative scenarios, to provide them with the choice of the best actions to be implemented in the river basin (Ono, 2008).

However, note that the challenge when developing an DSS is to meet the needs of those involved at different decision-making levels. Although there are numerous particularities, these systems must be able to: i) help users to develop their own models and identify the most important issues to manage the hydrographic basin of interest; ii) provide an initial view of the interrelationships between the different components of the system; and iii) facilitate communication and understanding by all those involved, so that they share the same vision (Loucks, 2006).

From these perspectives, the dialogue module is essential in communicating with the user, facilitating the participation of non-specialists in decision-making processes. This is of fundamental importance for river basin committees, as interaction takes place in this module, enabling information to be obtained, incorporating the judgments of interested parties and analyzing results to support decision-making processes (Braga, Barbosa & Nakayama, 1998; Porto & Porto, 2008; INBO & UNESCO, 2018).

Study area

The PCJ Basins are inserted in the Tietê River Hydrographic Basin, encompassing 76 municipalities (totally and partially inserted), being 93% in the territory of the State of São Paulo and 7% in the State of Minas Gerais. With approximately 15.300 km² of drainage area, the planning and management of water resources in the region can take place at five levels of detail: 39.430 otto-codified contribution areas (otto-basins); 225 contribution areas (CAs); 37 zones; 7 sub-basins and 3 main basins (Consórcio Proffil-Rhama, 2020).

With 5.85 million inhabitants (Fundação Agência das Bacias PCJ, 2020), this region is marked by a history of low *per capita* water availability and high demands, especially for supplying the MRC, which represents 54% of the total supply demand of the PCJ Basins. This complexity is intensified in water crisis scenarios, in which decision-making must be based on reliable data and information to manage existing conflicts and ensure that users' demand is met. In the water crisis experienced in 2014, for example, the use of data generated by the PCJ Basins telemetric system was essential to monitor the storage of the Cantareira System and the situation of water bodies in the region (Lopes, et al. 2019).

The Cantareira System is highlighted in the PCJ Basins, as four of the six reservoirs that comprise it are in the region's drainage area, and the water reserved in this system is used to supply approximately 10 million inhabitants of the MRSP and the PCJ Basins (Fundação Agência das Bacias PCJ, 2020). Considering that part of the water from some rivers in the Piracicaba River basin is transferred to the Alto Tietê basin because of that system, operating rules were established in 2017 (ANA/DAEE Resolução n. 925, 2017) aiming at meeting the requirements of the demands of the two regions.

The importance of monitoring the situation of water bodies is hence reinforced, citing as an example the monitoring of strategic points in the Atibaia River (in Atibaia/SP and Valinhos/SP) and in the Jaguari River (in Morungaba/SP). In these cases, the data are used to feed simulations and models for forecasting rainfall and flow (Consórcio Profill-Rhama, 2020; Almeida et al., 2019); to verify compliance with operating conditions and support decisions about the discharge of flows from the Cantareira System (Resolução ANA/DAEE n. 925, 2017); to alert users, PCJ Situation Room (PCJSR) and Civil Defense about possible risks; to assist in the operational management of users who catch water from their respective water body; and also to support the planning of the PCJ Basins, especially when assessing the criticality of the water balance, indicating the need for investments in structural and non-structural measures.

In order to make the decision process more robust, it is essential to integrate monitoring data with the DSS, which are enhanced with numerous functionalities, according to the users' needs. Next, the experience of the SSD PCJ is presented, a tool that has contributed to ensuring efficiency in the management of water resources in the PCJ Basins.

PCJ Basins Decision Support System – SSD PCJ

The DSS use for water resources management in the PCJ Basins was made possible in 2003 by an intention protocol signed between the State Secretariat of Energy, Water Resources and Sanitation of the State of São Paulo, the Alto Tietê Basin Committee (CBH-AT), the Piracicaba, Capivari and Jundiaí River Basin Committees (PCJ Committees), the State of São Paulo Department of Water and Electric Energy (DAEE), the State of São Paulo Basic Sanitation Company (Sabesp) and the Intercity Consortium of the Piracicaba, Capivari and Jundiaí River Basins (PCJ Consortium). The initial goal of the system was to optimize the use of public water sources.

In the second development stage, in 2007, the focus was integrating water allocation and quality models in a friendly georeferenced basis with data input and output, which could be exported to other software, such as text editors and spreadsheets. This tool was the basis for generating simulated scenarios for the PCJ Basins Plan 2010-2020 (Cobrape, 2010), enabling the assessment of the quantity and quality of surface waters.

The third stage began in 2011, with the creation of the Piracicaba, Capivari and Jundiaí River Basins Agency Foundation (PCJ Basins Agency). In this period, the SSD PCJ started to cover methodology and procedures for forecasting levels and flows in water bodies with a range of six hours to ten days.

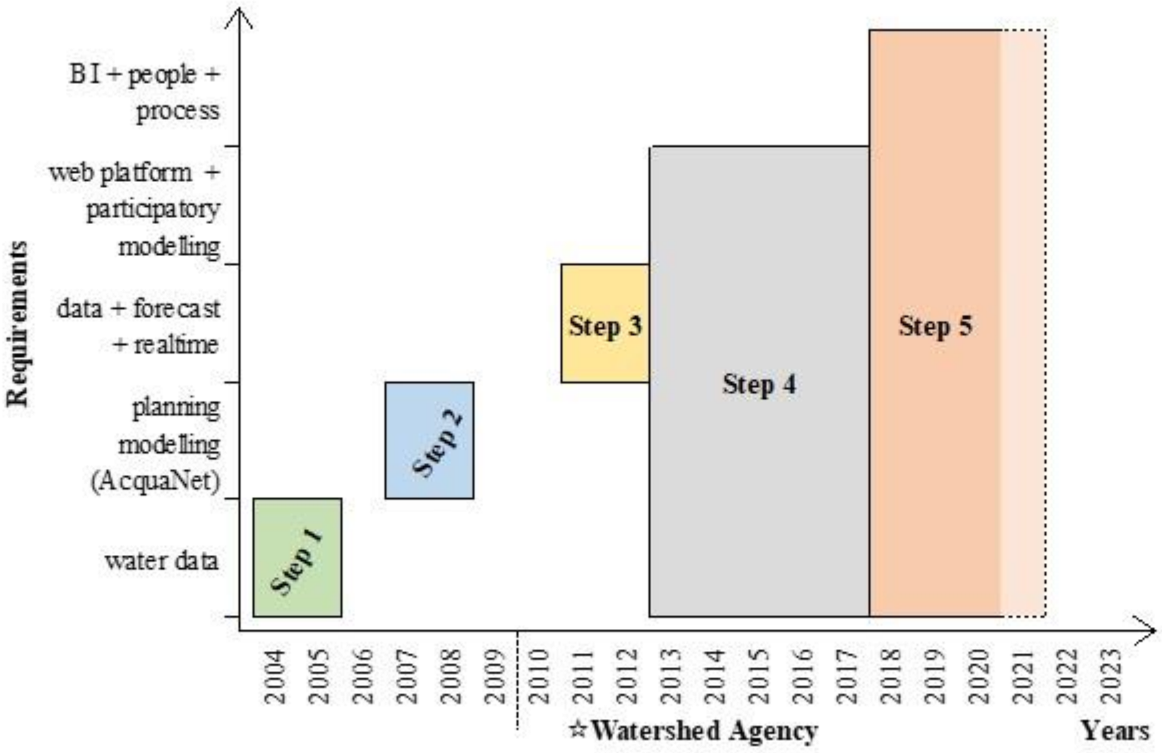
The fourth stage aimed to restructure and to improve the existing web decision support tools, which involved a deep code refactoring and the largest development so far. Furthermore, the databases of interest to the PCJ Basins were integrated and centralized in the system, and their automatic updating mechanisms were developed. Due to substantial changes, efforts were invested in training in using the system, with more than twenty training courses being carried out.

In the fifth stage – still in progress – the goal is to expand the capacity for collecting, analyzing, and making available information to support decisions and planning of water resources in the region. In this stage, as innovation, a local support team at the PCJ Basins Agency stands out, as well as keeping the routines maintenance and the continuous improvement of the system - with all its functionalities, tools, mathematical models, and programming languages -, always considering technologies more suited to the Foundation's reality.

In Figure 1, the stages of development of the SSD PCJ are presented by different functionalities. In general, the direction of the functional axis corresponds to the increase in the complexity of both: the solution and the understanding of the problem.

Figure 1

SSD PCJ development timeline



Source: The authors (2021).

Figure 1 shows that the development started with a data-oriented DSS for water resources, to solve the problems of access to information by the water resources system stakeholders. That was followed by a model-oriented DSS that could generate planning alternatives and support decisions related to the PCJ Basins Plan 2010-2020. Later, flood events in the PCJ Basins, in 2009-2010, resulted in the prioritization of a data-driven DSS and real time forecasting models, supporting decision-making in the face of flood occurrences.

The creation of the PCJ Basins Agency, in 2009, played an important role in the development process of the SSD PCJ, as the actions related to decision support began to be coordinated. There was thus the fusion of learning and functionalities of previous projects, and the inclusion of participatory modeling, which aims to make decisions based on methodologically standardized results accepted by all stakeholders (Basco-Carrera, Warren, Beek, Jonoski, & Giardino, 2017). This led to the planning process of the PCJ Basins to be streamlined, with the availability of information and results of possible actions to be implemented in the basin. This opened the possibility for everyone involved to visualize, create, and share different resulting scenarios, testing their assumptions before starting discussions with the PCJ Committees and water resources management agencies.

With the tool potential and the need to expand the Foundation's capabilities, at the current stage, the project is no longer just a development project, but also has an operational character, aiming to manage water resources to promote water security in the region. Thus, it began to involve people and processes to generate information on water resources including, for example, those related to real-time monitoring of water conditions, hydrological and management forecasts, and support for decision-making processes in the basins plan.

As explained before, the successive stages of development of the SSD PCJ considered the principles and objectives of the WRIS and the DSS (ANA, 2016; IOWater, 2013; Lei Nº. 9.433,1997), particularly in relation to the unified coordination of data and information obtained in a decentralized way. As a result, this system consists of a friendly dialog module that allows easy user-system interaction, a robust database (comprising data from different sources) and a quali-quantitative mathematical model that allows the simulation of scenarios and evaluating water uses and interferences.

The SSD PCJ is also in accordance with what Denzer (2005) recommended, given that it includes complex algorithms; it is also capable of unifying different data, tools, and methodologies in a single interface, contributing to achieving the goals of both operational management and investment planning, listed by Lima (2007) and INBO and UNESCO (2018). The fact of its being online, and public is very important for democratizing the access to data and information, also being relevant to ensure future integration with other management tools.

Therefore, the application of this system to the PCJ Basins Plans 2010-2020 and 2020-2035 (Cobrape, 2010; Consórcio Profill-Rhama, 2020), stands out for having enabled the current and future assessment of water resources quali-quantitative conditions, providing subsidies to better plan actions, to be carried out by the different actors in the region.

Another highlight regards the training activities and maintenance of the local team at the PCJ Basins Agency, whose main objective is the participatory modeling described by Basco-Carrera (2017), and the approach of the teams responsible for the system with the users. As a result, the problems to be solved are better understood and, consequently, the needs of those involved at different decision-making levels can be met more effectively.

Each of the system sections – Monitoring, Maps and Modeling – are detailed as follows, discussing their particularities and contributions in supporting the management and planning of water resources in the PCJ Basins.

SSD PCJ: monitoring module

The monitoring of the situation of the PCJ Basins began in the 1930s, with pluviometric and fluviometric measurements at strategic points. With the advancement of technology, the existing monitoring networks were redesigned to comply with current objectives. Thus, the current records of the PCJ Basins Agency indicate 202 activated and non-activated monitoring points in the region, of which 162 belong to water resources management agencies and 40 belong to partners, who share their data collaboratively. Among these, 87 are quantitative monitoring points, and 115 are qualitative.

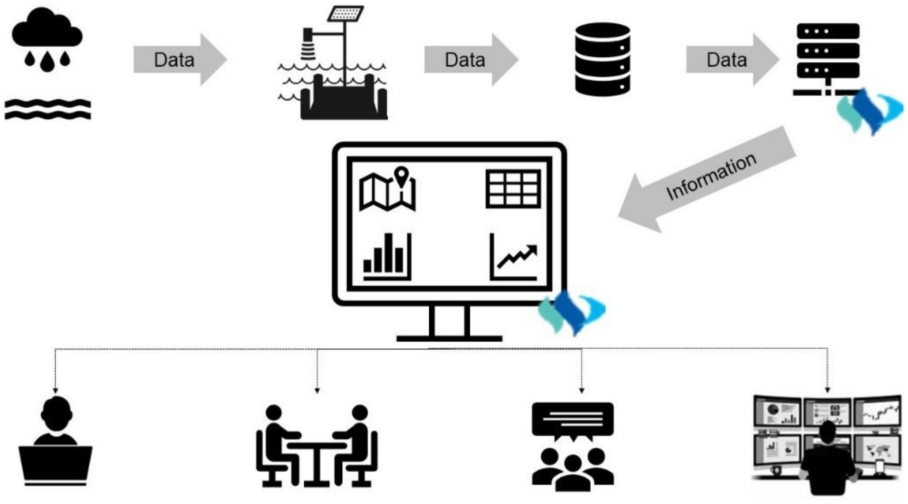
The quantity stations monitor rain, river level and flow. In the case of precipitation, monitoring employs three methods – pluviometers, São Paulo Meteorological Radar[1] and Integrated Precipitation System (Siprec[2]), described in Almeida et al. (2019) –, thus resulting in three parameters: rain at the point (rain gauge), radar rain (São Paulo Meteorological Radar) and integrated rain (Siprec). In the monitored water bodies, the fluviometric level value is measured and transformed into flow, by rating curves. The qualitative stations monitor several parameters (conductivity, Biochemical Oxygen Demand, pH, dissolved oxygen, temperature, etc.), due the different objectives of each evaluation.

This monitoring is essential for managing the PCJ Basins, as it has several purposes, consistent with those pointed out by Longo Júnior (2011) and ANA (n.d.), such as: monitoring changes in water quality and quantity; supporting studies of critical hydrological events; alerting for possible adverse impacts; feeding simulation models; assessing compliance with regulatory standards; integrating it with management tools; supporting decision-making processes; and for both real time management and planning of watershed, etc.

Due to its importance, all the data monitored in the PCJ Basins (including those collected from non-activated stations) are stored in the SSD PCJ database, and then processed to be publicly available at its online interface, through maps and monitoring modules (Figure 2).

Figure 2

Monitoring data and information flow



Source: The authors (2021).

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[1] Radar owned by DAEE. It is on the Ponte Nova Dam, between Salesópolis and Biritiba-Mirim (SP).

[2] The Siprec uses radar mosaic, satellite, and a rain gauge network.

Figure 2, allows observing that the monitoring data and information flow starts at the monitoring points, with the acquisition of data by the measuring equipment. This data is stored in a database and later processed by the SSD PCJ, being then transformed into information, which is made available on the online interface. Information can be consulted in maps, tables or column and line graphs by different users (water resources management agencies, Situation Room, river basin committees, users of water resources etc.), thus supporting their analyses, studies, and decisions.

Such functionalities allow users to simultaneously visualize different parameters in the same query, for one or several monitoring points, spatially located. Thereby users can carry out comparative and integrated analyses (including quali-quantitative) of a large amount of data, regardless of its type, source, or periodicity. This SSD PCJ integration feature is the main difference from other WRIS in Brazil.

The integration of all the data generated in the SSD PCJ, regardless of their particularities (source, type, data acquisition frequency etc.), is ensured by the structured SSD PCJ database. According to Tercini et al. (2019) and Goodall, Horsburgh, Whiteaker, Maidment and Zaslavsky (2008), water resources monitoring data have three-dimensional characteristics, in other words, it is possible to correlate three attributes: location, parameter and observation time. With this cubic structure, each data stored in the database is always associated with a **station**, a **parameter,** and the **date** when the measurement took place, thus allowing the integration of data from different sources.

As a result, the monitored data is made available to the public in maps and monitoring modules, which have different aims. The maps section provides spatial information to users in a simple way, especially about the real time monitoring of water bodies. The monitoring module aims to make available all the monitored data (historical series and real time), enabling users to carry out different analyses to support their decision-making processes.

This module is divided into two parts, which also have different characteristics and objectives: The first one – “Aggregated data” – provides summary results, for comparing data of several monitoring stations, which are aggregated in different analysis periods; the second one – “Time series” – allows comparing of different parameters and stations on the same time scale.

Although each section has its own particularity, data search is generally made by monitoring station(s) (quantitative and/or qualitative), monitored parameter (rain at the point, flow, pH, turbidity, etc.), analysis period (time interval to be considered, e.g., last 24 hours, last 30 days etc.), time scale (hourly, daily, monthly, or annual) and aggregation calculation (instantaneous, sum, average, maximum, minimum, or median).

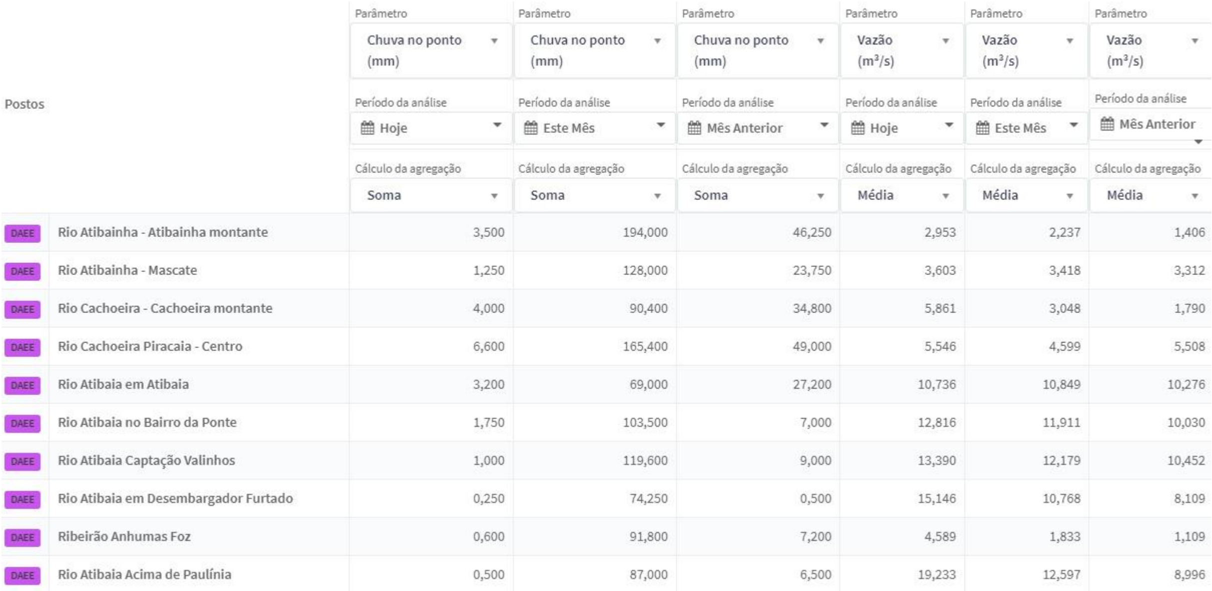
In both cases, the monitoring module provides user-system interaction, enabling users to promptly perform customized queries, manipulation, analyses and exportation of large amounts of data, as described by Russell et al. (2001). As a result, the information is made available in table and graph, allowing non-specialist users to have analytical tools to support management and planning actions, improving decisions about the PCJ Basins water resources, in line with Braga et al. (1998) and Porto and Porto (2008).

That is why the two sections in this module play different roles in supporting users' decisions. Whereas “Aggregated data” is relevant to compare different stations in different time periods, enabling evaluation in different places and periods, “Time series” is essential to evaluate the behavior of a certain monitored parameter over time, allowing for the identification of possible changes and trend analysis.

Figure 3 provides an example of the “Aggregated data” table, which contains information about “rain at the point” and “flow” for analysis period of “today”, “this month” and “previous month”. The monitoring stations are distributed in rows, and the columns represent parameters, analysis periods and aggregation calculation (sum of rain at the point and flow average).

Figure 3

“Aggregated data” table



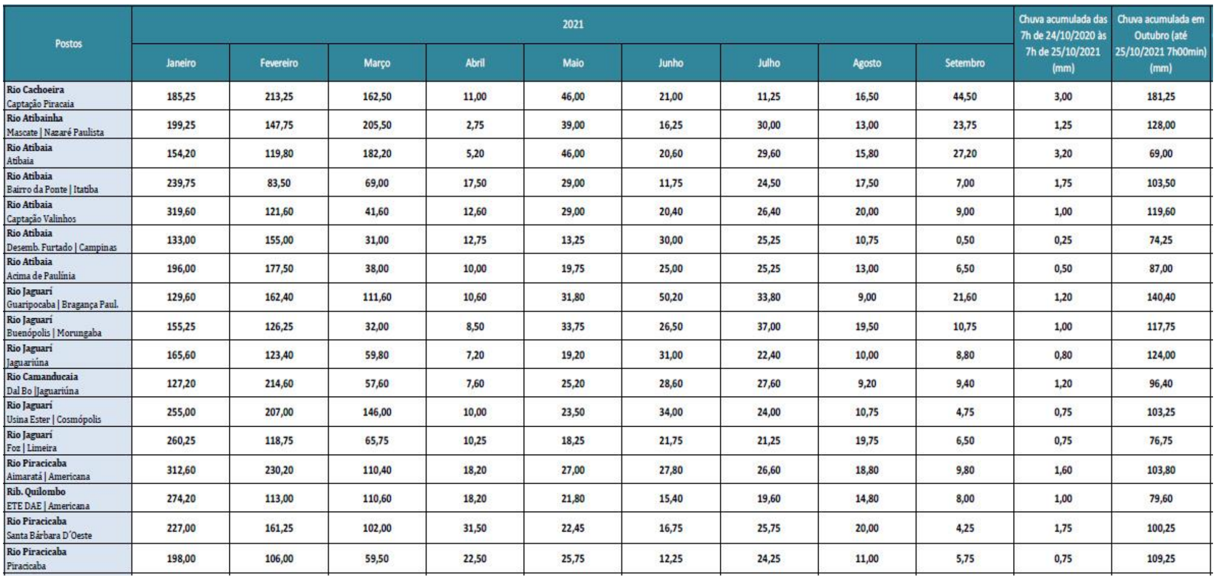
	Postos	Parâmetro Chuva no ponto (mm) Período da análise Hoje Cálculo da agregação Soma	Parâmetro Chuva no ponto (mm) Período da análise Este Mês Cálculo da agregação Soma	Parâmetro Chuva no ponto (mm) Período da análise Mês Anterior Cálculo da agregação Soma	Parâmetro Vazão (m^3/s) Período da análise Hoje Cálculo da agregação Média	Parâmetro Vazão (m^3/s) Período da análise Este Mês Cálculo da agregação Média	Parâmetro Vazão (m^3/s) Período da análise Mês Anterior Cálculo da agregação Média
DAEE	Rio Atibainha - Atibainha montante	3,500	194,000	46,250	2,953	2,237	1,406
DAEE	Rio Atibainha - Mascate	1,250	128,000	23,750	3,603	3,418	3,312
DAEE	Rio Cachoeira - Cachoeira montante	4,000	90,400	34,800	5,861	3,048	1,790
DAEE	Rio Cachoeira Piracaia - Centro	6,600	165,400	49,000	5,546	4,599	5,508
DAEE	Rio Atibaia em Atibaia	3,200	69,000	27,200	10,736	10,849	10,276
DAEE	Rio Atibaia no Bairro da Ponte	1,750	103,500	7,000	12,816	11,911	10,030
DAEE	Rio Atibaia Captação Valinhos	1,000	119,600	9,000	13,390	12,179	10,452
DAEE	Rio Atibaia em Desembargador Furtado	0,250	74,250	0,500	15,146	10,768	8,109
DAEE	Ribeirão Anhumas Foz	0,600	91,800	7,200	4,589	1,833	1,109
DAEE	Rio Atibaia Acima de Paulínia	0,500	87,000	6,500	19,233	12,597	8,996

Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 25, 2021).

Note in Figure 3 that this environment is relevant in comparative analyses of different stations in different periods of time, enabling the evaluation of water bodies at different times. When comparing it to Figure 4, observe that the structure of the table presented in this section is similar to the PCJSR bulletin, considered the key user in the participatory development of the SSD PCJ (fifth stage). The fact that this system integrates data from different entities and allows users to manipulate the data according to their own objectives, contributes to streamlining the process of gathering information and preparing reports and bulletins, in accordance with the purposes of WRIS (ANA, 2016).

Figure 4

PCJSR Daily Bulletin



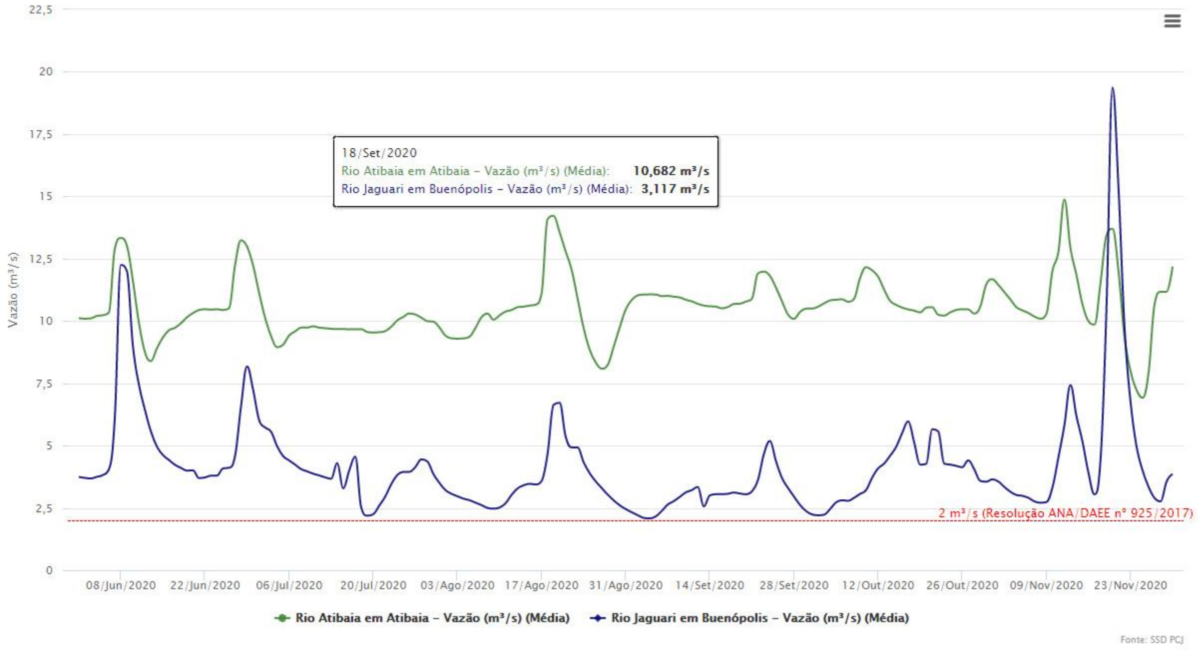
Postos	2021									Chuva acumulada das 7h de 24/10/2020 às 7h de 25/10/2021 (mm)	Chuva acumulada em Outubro (até 25/10/2021 7h00min) (mm)
	Janeiro	Fevereiro	Março	Abril	Maio	Junho	Julho	Agosto	Setembro		
Rio Cachoeira Captação Piracaia	185,25	213,25	162,50	11,00	46,00	21,00	11,25	16,50	44,50	3,00	181,25
Rio Atibainha Mascate | Nazaré Paulista	199,25	147,75	205,50	2,75	39,00	16,25	30,00	13,00	23,75	1,25	128,00
Rio Atibaia Atibaia	154,20	119,80	182,20	5,20	46,00	20,60	29,60	15,80	27,20	3,20	69,00
Rio Atibaia Bairro da Ponte | Itatiba	239,75	83,50	69,00	17,50	29,00	11,75	24,50	17,50	7,00	1,75	103,50
Rio Atibaia Captação Valinhos	319,60	121,60	41,60	12,60	29,00	20,40	26,40	20,00	9,00	1,00	119,60
Rio Atibaia Desemb. Furtado | Campinas	133,00	155,00	31,00	12,75	13,25	30,00	25,25	10,75	0,50	0,25	74,25
Rio Atibaia Acima de Paulínia	196,00	177,50	38,00	10,00	19,75	25,00	25,25	13,00	6,50	0,50	87,00
Rio Jaguarí Guaripocaba | Bragança Paul.	129,60	162,40	111,60	10,60	31,80	50,20	33,80	9,00	21,60	1,20	140,40
Rio Jaguarí Buenópolis | Morungaba	155,25	126,25	32,00	8,50	33,75	26,50	37,00	19,50	10,75	1,00	117,75
Rio Jaguarí Jaguariúna	165,60	123,40	59,80	7,20	19,20	31,00	22,40	10,00	8,80	0,80	124,00
Rio Camanducaia Dal Bo |Jaguariúna	127,20	214,60	57,60	7,60	25,20	28,60	27,60	9,20	9,40	1,20	96,40
Rio Jaguarí Usina Ester | Cosmópolis	255,00	207,00	146,00	10,00	23,50	34,00	24,00	10,75	4,75	0,75	103,25
Rio Jaguarí Foz | Limeira	260,25	118,75	65,75	10,25	18,25	21,75	21,25	19,75	6,50	0,75	76,75
Rio Piracicaba Aimaratá | Americana	312,60	230,20	110,40	18,20	27,00	27,80	26,60	18,80	9,80	1,60	103,80
Rib. Quilombo ETE DAE | Americana	274,20	113,00	110,60	18,20	21,80	15,40	19,60	14,80	8,00	1,00	79,60
Rio Piracicaba Santa Bárbara D´Oeste	227,00	161,25	102,00	31,50	22,45	16,75	25,75	20,00	4,25	1,75	100,25
Rio Piracicaba Piracicaba	198,00	106,00	59,50	22,50	25,75	12,25	24,25	11,00	5,75	0,75	109,25

Source: PCJSR (http://sspcj.org.br/, retrieved October 25, 2021).

In the case of “Time series”, the analysis aims at evaluating the evolution of different parameters and/or monitoring stations in the same analysis period and time scale. In Figure 5, we present an example of a graph of this section, showing the analysis of the average daily flow rates at the control stations in Atibaia/SP (“Rio Atibaia em Atibaia”, in green) and in Morungaba/SP (“Rio Jaguari em Buenópolis”, in blue), in the dry period (June 1 to November 30) of 2020. The abscissa axis is the analysis period, and the ordinate axis is the monitored parameter. To assist in the analysis of compliance with the operating rules of the Cantareira System (Resolução ANA/DAEE n. 925, 2017), the graph was configured to display the reference line (in red), indicating the limit of 2 m³/s.

Figure 5

“Time series” graph



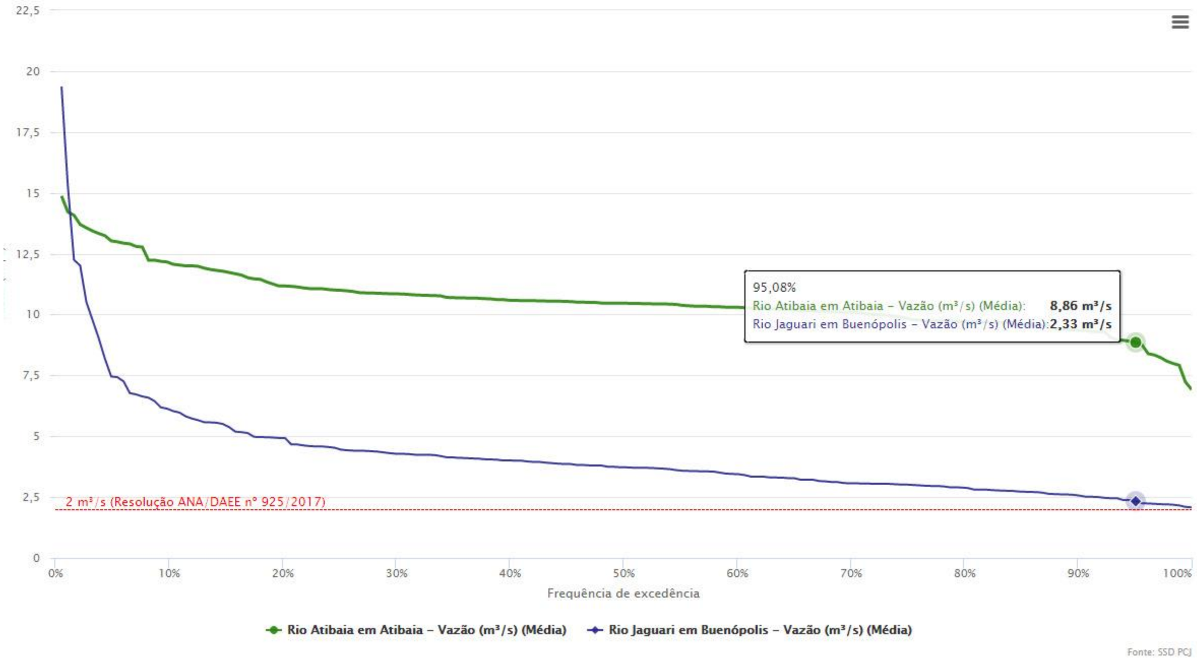
Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 19, 2021).

The “Time series” section has different objectives in comparison to “Aggregated data”, making it possible to assess the behavior and changes of monitored parameters over time. In order to complement the temporal analyses, the user can also consult the permanence curve, which is important in hydrological analyses, as it presents the cumulative relative frequency of river flows in a given location, making it possible to assess the occurrence of extreme variations in the river flow and the percentage of time in which the water body flow is within a given range (Collischonn, 2013).

Figure 6 presents the permanence curve of the previous query, indicating that the minimum flow established in the operating rule (Resolução ANA/DAEE n. 925, 2017) was respected throughout the analyzed period, and that, in 95% of the time (commonly used reference), the average flow in “Rio Atibaia em Atibaia” (in green) is greater than approximately 8.9 m³/s, and in “Rio Jaguari em Buenópolis” (in blue), greater than 2.3 m³/s. It can also be seen that the effect of regularizing the Cantareira System is greater at the station located in Atibaia/SP.

Figure 6

Permanence curves of Atibaia (Atibaia/SP) and Jaguari (Morungaba/SP) rivers, obtained in "Time series"



Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 25, 2021).

As previously shown, the SSD PCJ monitoring module tools allow water resources management agencies, river basin committees, Situation Rooms and users of water resources to carry out analyses on the occurrence and distribution of precipitation in the PCJ Basins, on the quality and quantity conditions of water bodies over time, and on the behavior of rivers in the face of climatic variability and reservoir operations, thus ensuring that monitoring is used in accordance with the main objectives listed by Longo Júnior (2011) and ANA (nd). This information and analysis are essential in the context of many discussions, such as debates on the occurrence of extreme weather events, resilience and sustainability of water resources and the need to update current legal regulations.

SSD PCJ: maps module

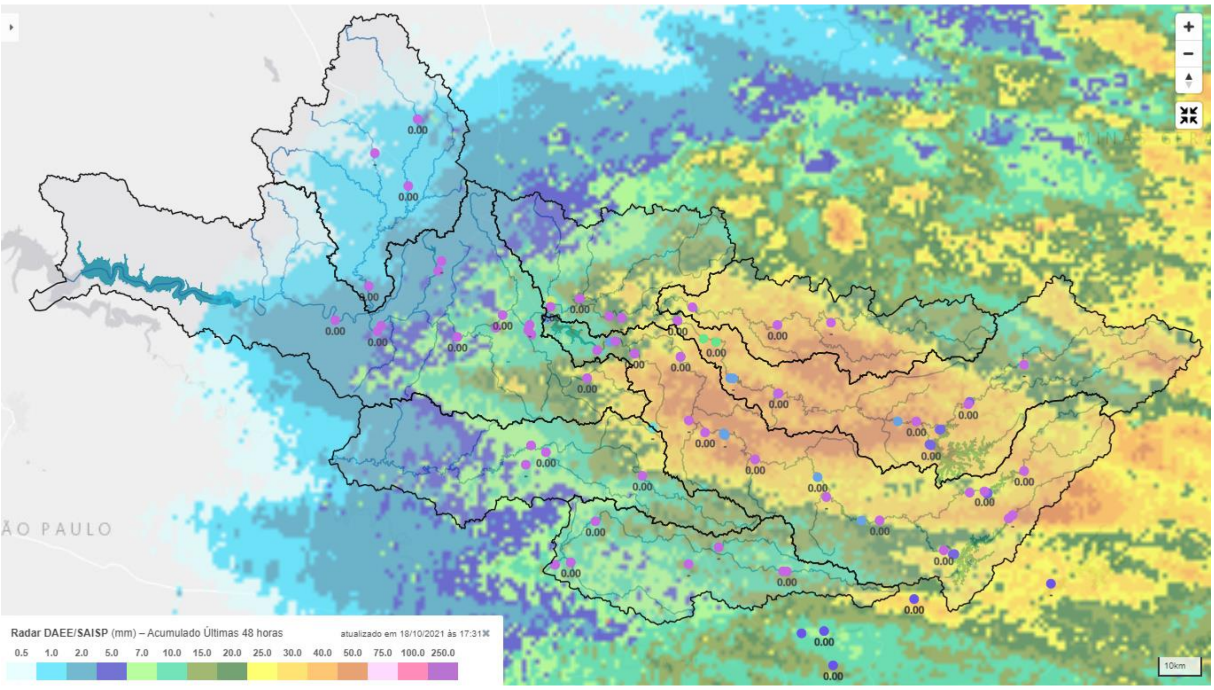
The maps section contains resources and GIS functionality in an interactive map, on which various layers and background maps are available. Interactivity can be performed by various actions (e.g., selection of layers), allowing users to immediately have a summarized view of the hydrological monitoring network and the situation of the PCJ Basins. In this module, the integration between database, GIS and real time monitoring systems is evident, as described by Denzer (2005), which results in the simplified dissemination of large amounts of spatially organized data, ensuring the suggestions of Russell et al. (2001).

One of the main layers is "Stations", where all monitoring points are listed as markers, allowing visibility on the map. Users can choose to display the label, i.e., the value of the monitored parameter (sum of rain at the point, sum of radar rain, level, flow, pH, turbidity, etc.) and the time interval to be used for calculation (last data, last hour, last 24 hours, last 7 days, etc.), with additional options to edit the display mode (bold, font size and color, opacity and overlay).

Besides the "Stations" layer, the "Radar DAEE/Saisp" deserves to be highlighted, as it allows users to consult different images from the São Paulo Meteorological Radar, including the latest animation, accumulated (last hour, last 24 hours, in a specific event, etc.), the precipitation displacement forecast, etc. Likewise, it is possible to customize it, changing the opacity of the images (Figure 7).

Figure 7

Maps module – Rain accumulated in 48 hours (São Paulo Meteorological Radar)



Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 18, 2021).

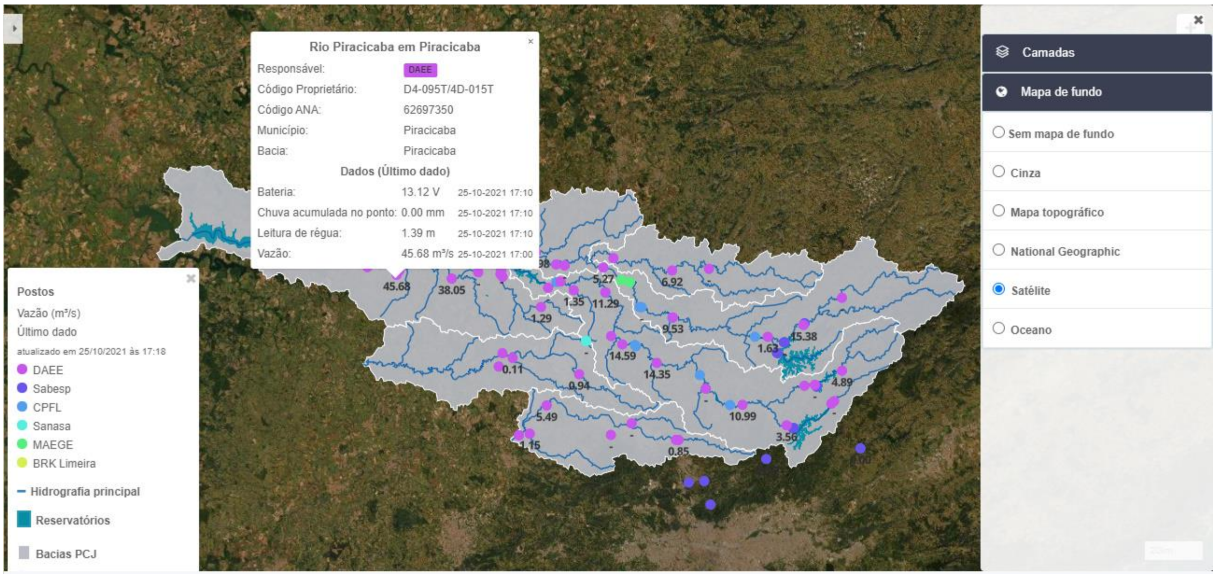
There are also the layers "Main Catchments", "Main Releases", "Main Hydrography", "Municipalities", "Reservoirs", "Contribution Areas" and "PCJ Basins", which were extracted from the cartographic base of the PCJ Basins Plan 2020-2035 (Consórcio Profill-Rhama, 2020). These layers also enable to perform several editing actions, such as changing the color of the icon, opacity, filling, border, size, etc. In addition, the background map can be customized, based on six thematic map options ("No map", "Gray", "Topographic map", "National Geographic", "Satellite" and "Ocean"), which can be selected and used together with the other layers, aiming to optimize the user experience in the visualization and presentation of the information.

Another highlight is the possibility of interaction on the map itself, allowing the user to directly and simply obtain additional information about the interest layer. When passing the mouse cursor over a monitoring station, for example, its name is shown on the screen, and when clicking on the station, a summary sheet containing information is shown, such as the entity responsible for the station, codes (owner and ANA's code), its location (city and sub-basin) and the respective data as selected in the editing of the layer "Station" (parameter and time interval), and by default the average flow data of the last hour is shown. In the other layers, it is also possible to view a set of information, such as the river class in the "Main Hydrography", the area of the municipality and its insertion in the PCJ Basins.

Figure 8 illustrates the interaction on the map with monitoring station information, with the background map "Satellite".

Figure 8

Interactivity in the "Stations" layer



Rio Piracicaba em Piracicaba

Responsável: DAEE
Código Proprietário: D4-095T/4D-015T
Código ANA: 62697350
Município: Piracicaba
Bacia: Piracicaba

Dados (Último dado)

Bateria:	13.12 V	25-10-2021 17:10
Chuva acumulada no ponto:	0.00 mm	25-10-2021 17:10
Leitura de régua:	1.39 m	25-10-2021 17:10
Vazão:	45.68 m³/s	25-10-2021 17:00

Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 25, 2021).

This module also has a drawing and measurement tool, which allows the user to add markers, and draw lines and polygons, indicating their distance and area.

With the various existing tools and interactions, users have straight and very simple access to updated and spatially allocated information, which has been synthesized from a large amount of data. Users' experiences with this module indicate that such functionalities are important to have an immediate vision of the PCJ Basins, optimizing the evaluation of possible atypical situations.

SSD PCJ: modeling module

The modeling module[3] consists of a quali-quantitative mathematical model structured in an AcquaNet flow network, developed by the Laboratory of Decision Support Systems in Environmental Engineering and Water Resources (LabSid). This model is based on the Out-of-Kilter algorithm, which has the objective function (1) to minimize the costs of water transfer between the nodes of the model's network, obeying imposed restrictions (2) and (3) (LabSid, 2015). It enables the analysis of complex water systems, by flow networks associated with a specific database, providing scenarios simulation and generation of results on the various uses and interferences that exist or may be implemented in a hydrographic basin (Carvalho, Méllo Júnior, Schardong, & Porto, 2009; Labsid, 2015; Pedrozo et al., 2019).

Objective function:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} \times q_{ij} \qquad (1)$$

Subject to the following restrictions:

$$\sum_{i \in I_j} q_{ij} - \sum_{k \in O_j} q_{jk} = 0 \qquad (2)$$

$$I_{ij} \leq q_{ij} \leq U_{ij} \qquad (3)$$

Where:

- q_{ij} = average flow between nodes i and j during the time interval considered;
- c_{ij} = unit cost, which can be monetary or a weighting factor that represents water rights or operational priorities (negative cost is treated as a benefit or priority);
- I_j = set of all nodes with arcs ending at node j;
- O_j = set of all nodes with arcs that originate at node j;
- I_{ij} = minimum flow in the arc (i, j);
- U_{ij} = maximum flow in the arc (i, j).

---

[3] Access restricted to specific users.

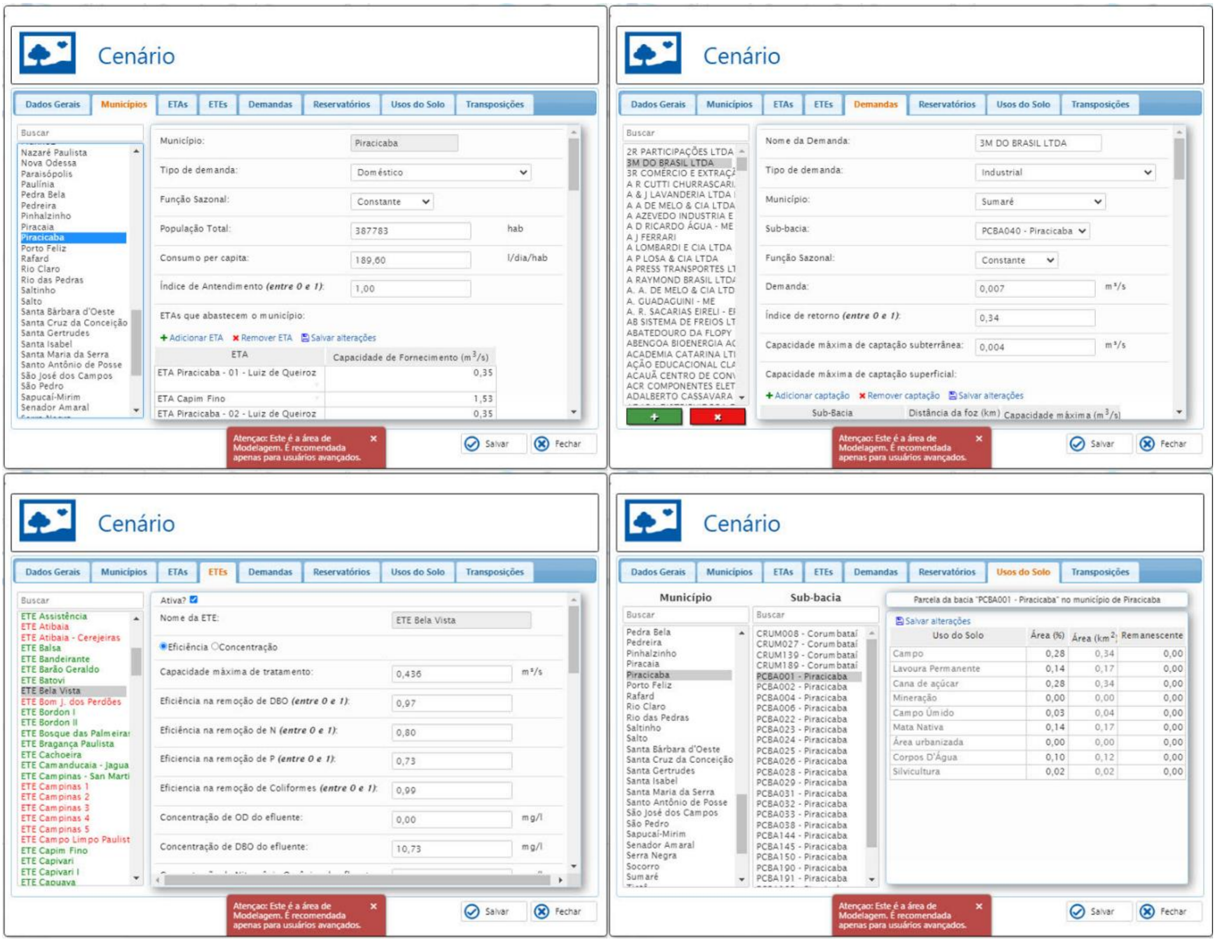
As AcquaNet is an integrated model, in addition to water allocation, the quality module can also be coupled. Thereby the system additionally has an advection, dispersion and decay model to calculate the water quality parameters (dissolved oxygen, biochemical oxygen demand, coliforms, nitrogen series and organic and inorganic phosphorus), which were considered in its conception, allowing simulating quality changes in the river stretches, depending on water availability. This functionality reiterates that the SSD PCJ contributes to improving decision processes, given that the scenarios permit to evaluate the best alternative to ensure the multiple use of water in adequate quality standards, in line with ANA (2016), Ono (2008) and Porto and Porto (2008).

In the SSD PCJ, the PCJ Basins are represented by 225 CAs, defined from an Otto-codified hydrographic base. All the calculations of quali-quantitative models, water balance and water quality simulation are performed for each of the sub-basins; that is, all the demands, releases and other information are grouped by CAs (Consórcio Profill-Rhama, 2020).

To create a scenario, it is necessary to manually load the data into the interface (Pedrozo et al., 2019). As an example of input data, the following are cited: urban population of municipalities, sewage supply and treatment rates, distribution loss rates, efficiency of treatment processes, specific demands of the various existing uses and use of soil etc. (Figure 9).

Figure 9

Scenario input data samples



Município: Piracicaba

Tipo de demanda: Doméstico

Função Sazonal: Constante

População Total: 387783 hab

Consumo per capita: 189,60 l/dia/hab

Índice de Antendimento *(entre 0 e 1)*: 1,00

ETAs que abastecem o município:

ETA	Capacidade de Fornecimento (m^3/s)
ETA Piracicaba - 01 - Luiz de Queiroz	0,35
ETA Capim Fino	1,53
ETA Piracicaba - 02 - Luiz de Queiroz	0,35

Atençao: Este é a área de Modelagem. É recomendada apenas para usuários avançados.

Nome da Demanda: 3M DO BRASIL LTDA

Tipo de demanda: Industrial

Município: Sumaré

Sub-bacia: PCBA040 - Piracicaba

Função Sazonal: Constante

Demanda: 0,007 m^3/s

Índice de retorno *(entre 0 e 1)*: 0,34

Capacidade máxima de captação subterrânea: 0,004 m^3/s

Capacidade máxima de captação superficial:

Sub-Bacia	Distância da foz (km)	Capacidade máxima (m^3/s)

Atençao: Este é a área de Modelagem. É recomendada apenas para usuários avançados.

Ativa? ☑

Nome da ETE: ETE Bela Vista

● Eficiência ○ Concentração

Capacidade máxima de tratamento: 0,436 m^3/s

Eficiência na remoção de DBO *(entre 0 e 1)*: 0,97

Eficiência na remoção de N *(entre 0 e 1)*: 0,80

Eficiencia na remoção de P *(entre 0 e 1)*: 0,73

Eficiencia na remoção de Coliformes *(entre 0 e 1)*: 0,99

Concentração de OD do efluente: 0,00 mg/l

Concentração de DBO do efluente: 10,73 mg/l

Atençao: Este é a área de Modelagem. É recomendada apenas para usuários avançados.

Parcela da bacia "PCBA001 - Piracicaba" no município de Piracicaba

Uso do Solo	Área (%)	Área (km^2)	Remanescente
Campo	0,28	0,34	0,00
Lavoura Permanente	0,14	0,17	0,00
Cana de açúcar	0,28	0,34	0,00
Mineração	0,00	0,00	0,00
Campo Úmido	0,03	0,04	0,00
Mata Nativa	0,14	0,17	0,00
Área urbanizada	0,00	0,00	0,00
Corpos D'Água	0,10	0,12	0,00
Silvicultura	0,02	0,02	0,00

Atençao: Este é a área de Modelagem. É recomendada apenas para usuários avançados.

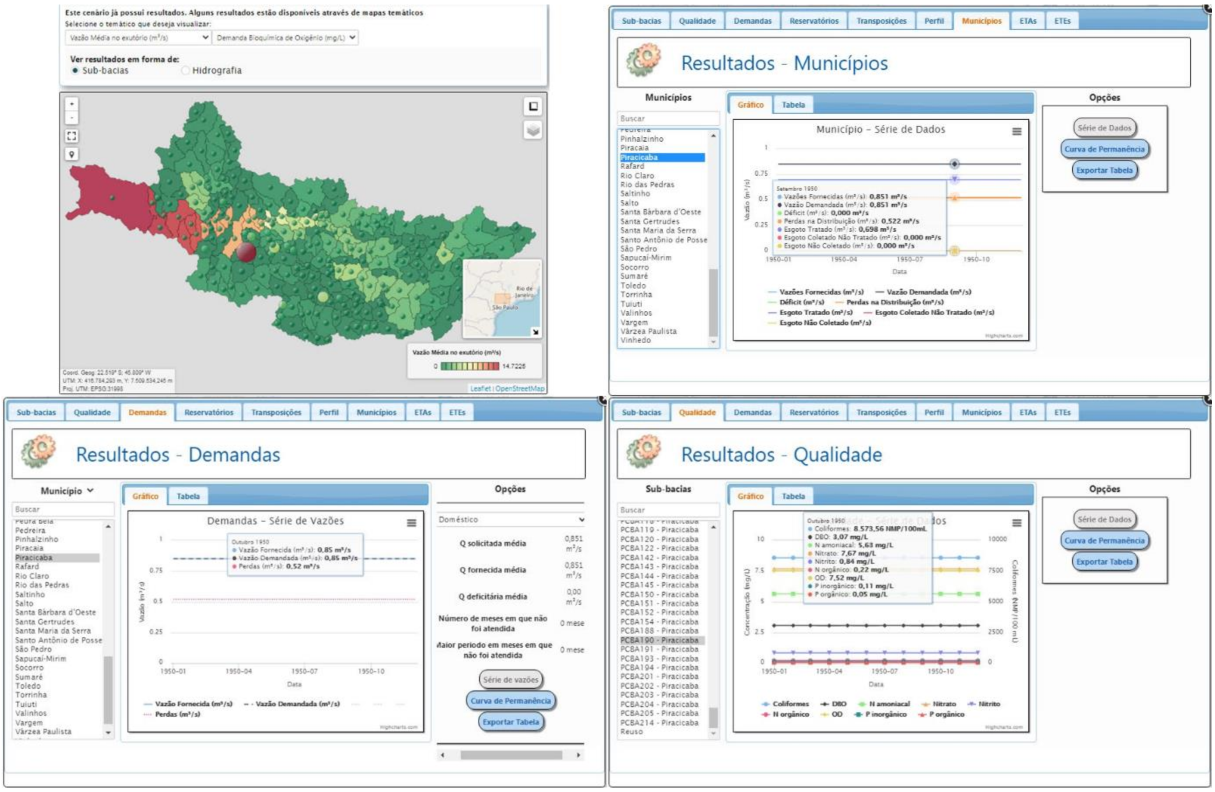
Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 16, 2021).

The model also has a set of “general data”, considered in all the scenarios as a background, i.e., the general database that impacts the simulations. It contains data on natural flows, demand groups (irrigation, industrial, domestic, animal watering, private urban), the details of reservoirs and transpositions, etc. These data do not characterize the scenarios but are basis that provides inputs for model simulations and calibration.

After loading the data and carrying out the simulations, the results can be analyzed at different scales – municipal, water and sewage treatment plants, specific demands made for that scenario and in intermediate stretches of a sub-basin (Consórcio Profill-Rhama, 2020). Figure 10 shows an example of results.

Figure 10

Scenario results samples



Source: SSD PCJ (https://ssd.baciaspcj.org.br/, retrieved October 16, 2021).

This module was extensively used in the PCJ Basins Plan 2020-2035 (Consórcio Profill-Rhama, 2020) in the simulations of future scenarios (2025, 2030 and 2035), to assess the impacts of interventions and forecasted demands on the quantity and quality of water, providing subsidies for planning actions to be implemented in the region, as highlighted by Lima (2007) and INBO & UNESCO (2018). To generate such scenarios, the model was fed with data monitored by the municipalities and water resources management agencies, in addition to the forecast of investments in the sanitation sector, from the expansion of sanitary sewage systems to the implementation of new reservoirs and reduction of rates of water losses in distribution, integrating information both on water and on the factors involved in management, corroborating the view of Moran et al. (2020).

Although the base of models is often extolled in the literature - composed of the mathematical models used in scenario simulation -, it is worth emphasizing that this type of system must be considered by the interrelationship of all its modules, to guarantee that all the information listed by Moran et al. (2020) are in fact integrated. In the case of SSD PCJ, for example, the different sections – Monitoring, Maps and Modeling – are directly or indirectly correlated.

In this context the use of SSD PCJ in the Basin Plan is not limited to simulating quali-quantitative future scenarios, as its main challenge concerns monitoring the implementation of actions and the resulting impacts. Thus, there is a close relationship of the "Monitoring" section with the implementation of the Plan, since the continuous monitoring of the situation of water bodies subsidizes the follow-up of the compliance with their classification classes, indicating if the planned actions are being effective, or if there is a need for adjustments so that the defined goals are achieved.

Conclusion

The analyses presented highlighted the complexity of the water resources management process, emphasizing the importance of consistent acquisition of hydrological data and structure of robust and reliable database, which support water basins planning and management. In this context, the SSD PCJ is an important tool to support the decision-making process in the PCJ Basins area, providing the integration of a large amount of data, regardless of its type, source, or periodicity.

This enables to visualize and to analyze data from the interest area in a single interface, reducing the time spent on data acquisition and thus optimizing the analysis and actions of several users. In addition, this system makes historical and real time data publicly available, allowing comparisons between different periods and monitoring points, supporting both operational management and planning actions for water resources.

The SSD PCJ has characteristics that enhance its application in water resources management, in line with the principles and objectives of WRIS and DSS, especially to support management tools development, decentralization of data and information acquisition, and transparency in the use of the system, with the public availability of updated data and information in an online interface.

As this work has shown that the three interrelated modules of the system contribute significantly to the management actions of the PCJ Basins, the experiences described here can be replicated in other river basins, contributing to the effectiveness of the management and planning of water resources. The executing agency, in addition to acquiring or developing a software with the requirements discussed here, will have to use a service that extract data from suppliers and input them at the proposed system, and also have a qualified professional to interpret them. There are clearly several technical challenges to be explored for standardizing the nomenclature of hydrological variables and files for exchanging hydrological information between systems.

Note that systems as the one presented here, once implemented, and used as a tool for river basin management, gain several attributions, such as: evaluation of indicators and/or reference values of critical situations of water scarcity or water quality; identification of risk situations and issuance of alerts to minimize adverse impacts; provision of useful information for inspection processes, proposition of regulatory standards and investment planning; etc. Therefore, the use of systems similar to the SSD PCJ in other hydrographic basins can contribute to the expansion of the management capacity, mainly due to the structure of the three-dimensional database and the integrated query and visualization of data of different sources.

Finally, the authors emphasize the need to expand multidisciplinary research that permeate the theme of information systems and water resources management, expanding knowledge on the theme and contributing to disseminating the numerous functions of this type of system. Therefore, future studies are recommended to evaluate how the dissemination of water resources information influences the behavior of the citizens of the hydrographic basin, and propose methodologies to standardize nomenclatures and files, to optimize the exchange of information between systems.

Acknowledgments

We would like to thank Luiz Roberto Moretti (in memorian) for his enormous contributions to the management of water resources in the PCJ Basins, LabSid/POLI/USP, FCTH, the PCJ Committees and the PCJ Basins Agency.

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