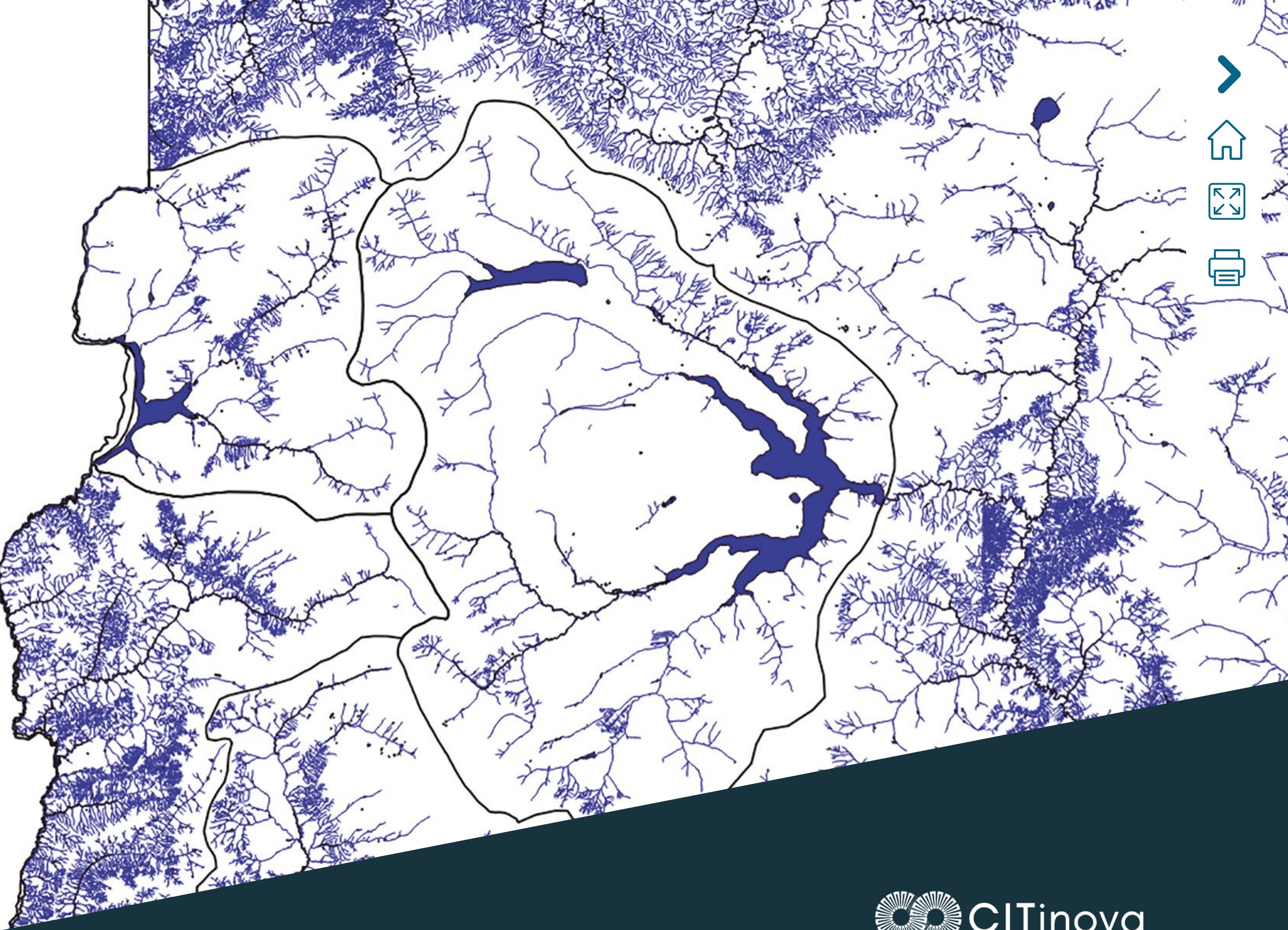

CITinova

Planejamento Integrado e Tecnologias para Cidades Sustentáveis

SUSTAINABILITY AND WATER RISK
OF STRATEGIC WATERSHEDS IN THE FEDERAL DISTRICT (BRAZIL)

Secretaria de Meio Ambiente

GDF
É tempo de ação.

STATE SECRETARIAT OF ENVIRONMENT OF FEDERAL DISTRICT
GOVERNMENT OF FEDERAL DISTRICT

SUSTAINABILITY AND WATER RISK

OF STRATEGIC WATERSHEDS IN THE FEDERAL DISTRICT (BRAZIL)

BRASÍLIA, 2021

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CONTENTS

EXECUTIVE SUMMARY

Sustainability and water risk are key aspects in the planning and sustainable management of watersheds, and in the establishment of effective adaptation measures against existing and future climate and human threats.

This book aims to estimate the degree of water sustainability and integrated sustainability in two strategic basins in the Federal District, Brazil; to assess water risk in a pilot basin; and to propose adaptation measures against the perceived threats.

The basins analyzed are the Paranoá River basin (1,056 km2), the Descoberto River basin (801 km2), and the Rodeador watershed (113 km2), which is a Sub-Basin of the second one and a pilot basin in the present study. The first two are regulated by reservoirs and the last one is unregulated.

In order to estimate the inter-annual water sustainability in the basins, the Water Resources System Dynamics (WRSD) Index of Xu et al. (2002), which balances annual water supply and demand, was selected. The WRSD was applied to the Descoberto, Paranoá and Rodeador Basins for the period between 1979-2017 and, particularly, to the Rodeador Basin for the assessment of two future scenarios of climate and water demand.

The future scenarios for the Rodeador Pilot Basin include the IPCC business-as-usual (RPC 4.5) and the pessimistic (RPC 8.5) pathways. For this purpose, precipitation and temperature projections for 2040 and 2070 were used, which were generated through the HadGEM2 model and regionalized through the Eta model, on a 5x5 km grid scale.

In the current scenario, the water sustainability of the Descoberto and Paranoá Basins are 0.32 and 0.66, respectively, which classify as medium water sustainability (0.2 <WRSD <0.8). The water sustainability of the Ribeirão Rodeador Basin ("Rodeador Basin"), set at 0.58 (medium) in the current scenario, drops to 0.2 (low) in the future climate and water demand scenarios.

To assess the intra-annual water risk of the Ribeirão Rodeador Pilot Basin, a stochastic water risk index (WRI) was developed based on the probability of system failure, where a random supply and demand of water was determined. The WRI was applied to the Ribeirão Rodeador Basin in the present and future scenarios (2040 and 2070), for the RPC 4.5 and 8.5 emission scenarios.

The water risk of the Ribeirão Rodeador Basin increases from 15.3%, in the present scenario, to amounts between 25% and 100% in 2040 and 2070, mainly due to a reduction of annual precipitation and an increase in temperature.

To assess integrated sustainability in the Paranoá and Descoberto Basins, the Watershed Sustainability Index - WSI (CHAVES; ALÍPAZ, 2007) was applied. The calculation of this index was possible through secondary data and questionnaires answered by managers, which fed in data regarding four indicators (hydrology, environment, livelihood and public policies)

In the current scenario (2015-2018), the Descoberto and Paranoá Basins present an average level of integrated sustainability (0.66 and 0.68, respectively). The factors that limited further sustainability in these basins were low per capita water availability and limited responsiveness to existing threats.

The uncertainties associated with the results obtained by both indexes were discussed. Aiming to reduce water risks and increase integrated sustainability in the basins studied, adaptation measures were proposed, following the state-of-the-art on the subject.

Due to its integrated and universal aspect, the methodology of the present study can be applied to other basins in the Federal District, allowing for the estimation of their sustainability and water risk, thus strengthening their planning and management processes.

ACRONYSMS

ADASA Regulatory Agency for Water, Energy and Basic Sanitation of the Federal Distric

ANA National Water and Basic Sanitation Agency

AR Administrative region

CAESB Federal District Environmental Sanitation Company

CITinova Integrated Planning and Technologies for Sustainable Cities

CPTEC Center for Weather Forecasting and Climate Studies

D water demand

DF Federal District

EPI Environmental Pressure Index

GCM General Circulation Model

GHG greenhouse gases

INPE National Institute for Space Research

GIS Geographic Information Systems

IPCC Intergovernmental Panel on Climate Change

MMA Ministry of the Environment

S water supply

SDG UN Sustainable Development Goals

P precipitation

PE potential evapotranspiration

p_f Probability of failure

PDCA Plan, Do, Check, Adapt

PNRH National Water Resources Plan

Q flow

Q95% 95% permanence streamflow

r correlation coefficient

RCM Regional Circulation Model

RCP Representative concentration path of greenhouse gases

RIDE Integrated Federal District and Surrounding Areas

SD standard deviation

SEMA/DF Department of the Environment of the Federal District

T temperature

VA Vulnerability Analysis

WH Water Sustainability

WR Water Risk

WRI Water Risk Index

WRSD Water Resources System Dynamics

WSI Watershed Sustainability Index

1 INTRODUCTION

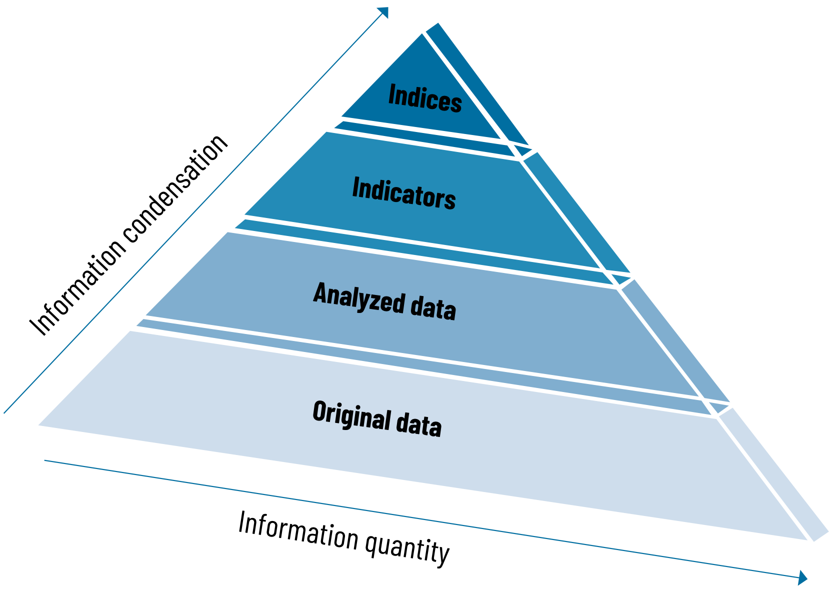
The environmentally and socially sustainable management of water and natural resources requires more than indicators that assess the environmental and hydrological impacts in a basin. It demands a new approach that goes beyond simply defining objectives and goals for planning and managing water and environmental resources.

This approach requires the analysis of the complex interrelationships between hydrological, ecological, social and economic processes, as well as the assessment of appropriate policies, actions, laws and institutions, across the entire decision-making process (SMITH; RAST, 1998).

Indicators have been used to support the planning, management and decision-making process of river basins. These indicators are a result of commitments made by countries regarding the integrated management of water resources and sustainability (GALLOPÍN, 1996).

In turn, indicators and indexes are tools that consolidate original data into analyzed data, and the latter into indicators and indexes (Figure 1.1), which facilitates the understanding of how complex systems work and the definition of appropriate policies and actions on the part of managers and civil society.

FIGURE 1.1 – OBTAINING INDICATORS AND INDEXES



Source: adapted from Goutzee et al. (1995)

According to the OECD (2008), indexes must be developed and selected taking into account a few basic criteria, such as relevance in policy terms, analytical robustness, and measurement capacity. Furthermore, their applicability and usefulness to governments and society are proportional to their ease of use and data availability.

Hence, sustainability and water risk indicators must pursue a systems' approach; identify interconnections between variables and cause-effect relationships; provide access to current conditions and trends in the basins; compare distinct locations and situations; and give warning of critical points (CHAVES, 2011).

Once the weaknesses relating to basin water safety and sustainability have been known, appropriate measures must be implemented to bring risks and threats down to reasonable values. This process of striving for sustainability and reducing water risk must follow the adaptive management approach, in which the experience gained in the process serves as a mean to improve future actions.

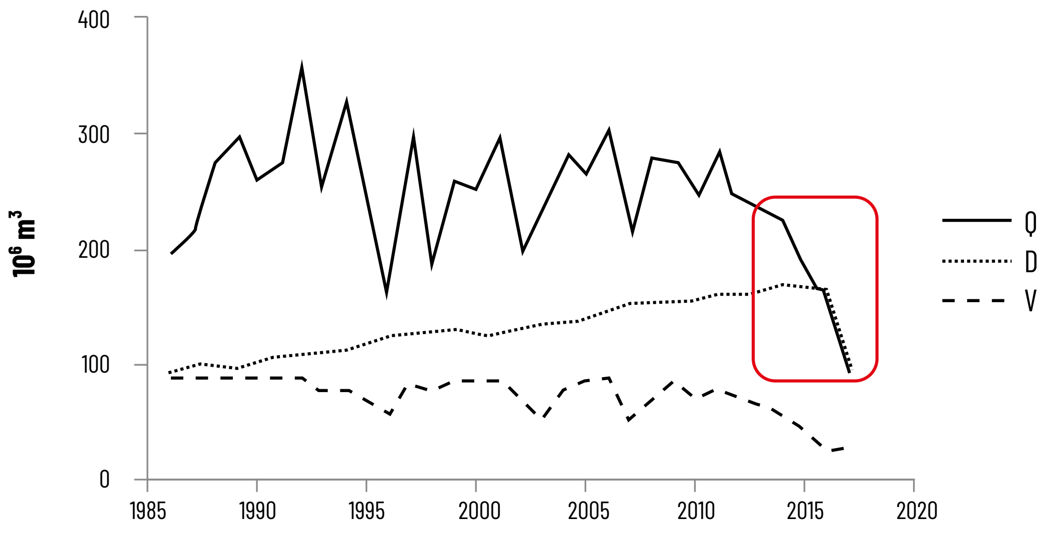
The integrated sustainability of river basins, in turn, is aligned with the Sustainable Development Goals of the United Nations - UN, particularly regarding SDG-6, which aims to ensure availability and sustainable management of water and sanitation for all.

Considering that the CITinova/CGEE Project aims to develop innovative technology solutions and offer methodologies and tools on integrated urban planning to assist public managers, encourage social participation and promote more equitable and sustainable cities, this study has focused on the development and application of robust indicators of water and integrated sustainability at the local level.

There are reasons why such local analysis is necessary. Due to the 2017 water rationing in the region, water security in the Federal District acquired an unprecedented dimension. This required a broader and more integrated approach from managers and civil society, which revealed the cause-effect relationship between threats and resulting actions in a transparent way. Furthermore, water risk is an important information in the decision-making process as it incorporates the intuitive combination of vulnerability and danger.

In the case of the Descoberto River basin, the determining factor for the recent collapse of the water supply system, even with its steady flow, was the occurrence of a climatic anomaly, known as the Hurst phenomenon, which was detected with reliable tests (Figure 1.2).

FIGURE 1.2 – ANNUAL INFLOW VOLUMES (Q), WATER DEMAND (D) AND STORED VOLUMES (V) IN THE DESCOBERTO RESERVOIR BETWEEN 1986 AND 2017. IN RED IS THE PERIOD OF PERSISTENCE OF LOW FLOWS (HURST), AND THE CORRESPONDING WATER RATIONING



Source: Chaves & Lorena (2019)

However, as anomalies are part of the regional climate variability, they must be taken into account in the basin planning and management process, especially in those that are strategic, as are the basins analyzed here.

Due to the impossibility of flow regulation, unregulated river basins, such as the Rodeador, are more affected by climate variability and increasing water demands than regulated basins, requiring complex and rarely effective regulatory frameworks. One of these basins is the Ribeirão basin in Brasília, where there are frequent water shortages.

Additionally, future climate scenarios in the Federal District for the next 50 years, resulting from distinct levels of greenhouse gas emissions, point to a decline in regional water availability. This threatens the water security and sustainability of the region's supply basins, and requires effective measures of risk prevention and adaptation.

Water availability is not the only factor that limits sustainability in these basins, water quality and other environmental, human and governance dimensions also affect it. In this sense, this study aimed to evaluate the vulnerabilities, pressures and threats to the three basins analyzed, as well as current responses and recommended adaptation measures.

Still far from presenting definitive solutions to the problems of water resources in the Federal District, the authors hope, through this study, to demonstrate the importance of the theme of sustainability and water risk, and to deepen this discussion in the various management spheres.

To facilitate the reading and understanding of the analysis given, this volume was divided into chapters, which cover main methodological aspects (Chapter 2), results achieved (Chapter 3), remaining uncertainties in the analysis (Chapter 4), planning and management recommendations (Chapter 5) and, finally, conclusions (Chapter 6).

It should be noted that this volume is a summary of five technical reports produced under the CITinova/CGEE Project. Consequently, to facilitate reading and understanding, part of the data and information contained therein has been left out, without prejudice to the main content.

2 METHODOLOGY

This Chapter presents the study methodology, including the description of the basins, the water and sustainability indicators, the development of the water risk model, the sources and processing of secondary data, and the different scenarios employed.

BASINS STUDIED

The basins analyzed in this study were those considered strategic watersheds for the water supply in the Federal District, and which were previously defined in the scope of the CITinova/CGEE Project.

Hence, the Paranoá, Descoberto, and Rodeador Basins were selected, the latter was also selected as a pilot for water risk analysis. A description of the basins is given below.

Paranoá River Basin

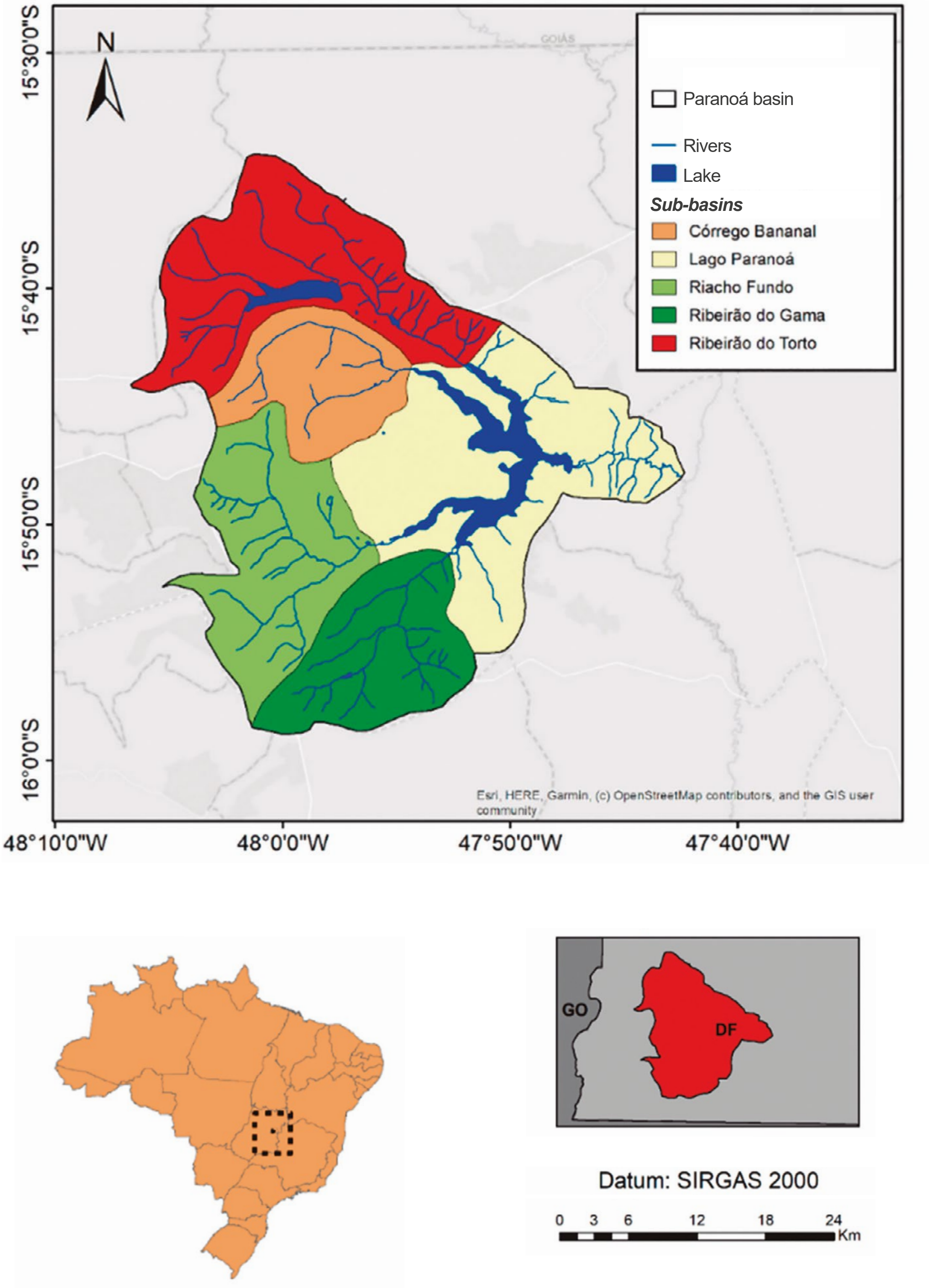
Located in the central region of the Federal District, the Paranoá River Basin has a total area of 1,056 km^2. It is a strategic basin where the city of Brasilia is located, and where 500,000 people live and work (Figure 2.1).

The Paranoá Basin receives an average of 1,500 mm of rain annually. It has a gentle-sloping topography and is predominantly covered by clayey Oxisols. The long-term average annual stream flow in the Paranoá River, at its dam, is 14 m^3/s. The predominant land use in the basin is urban, with remanescent areas of cerrado vegetation located in parks and natural reserves.

Built as an artificial lake in 1960, The Paranoá lake has an active volume of 35 hm^3, and generates energy, diluting treated sewage, besides serving as an important ecosystem for several species of fish and amphibians, and as a place of sport and leisure for the population of Brasília.

The *per capita* water demand in the Paranoá Basin is relatively high (1,400 inhabitants per hm^3). During the 2017 water crisis, the Paranoá lake became a source of supplementary supply for the city, reducing the pressure on the Descoberto System.

FIGURE 2.1 – PARANOÁ RIVER BASIN AND ITS MAIN SUB-BASINS



Source: Geoportal/DF

In the present study, the Water Sustainability (WRSD) and Watershed Sustainability (WSI) indexes were applied to the Paranoá River Basin the present scenario (2015-2018).

Descoberto River Basin

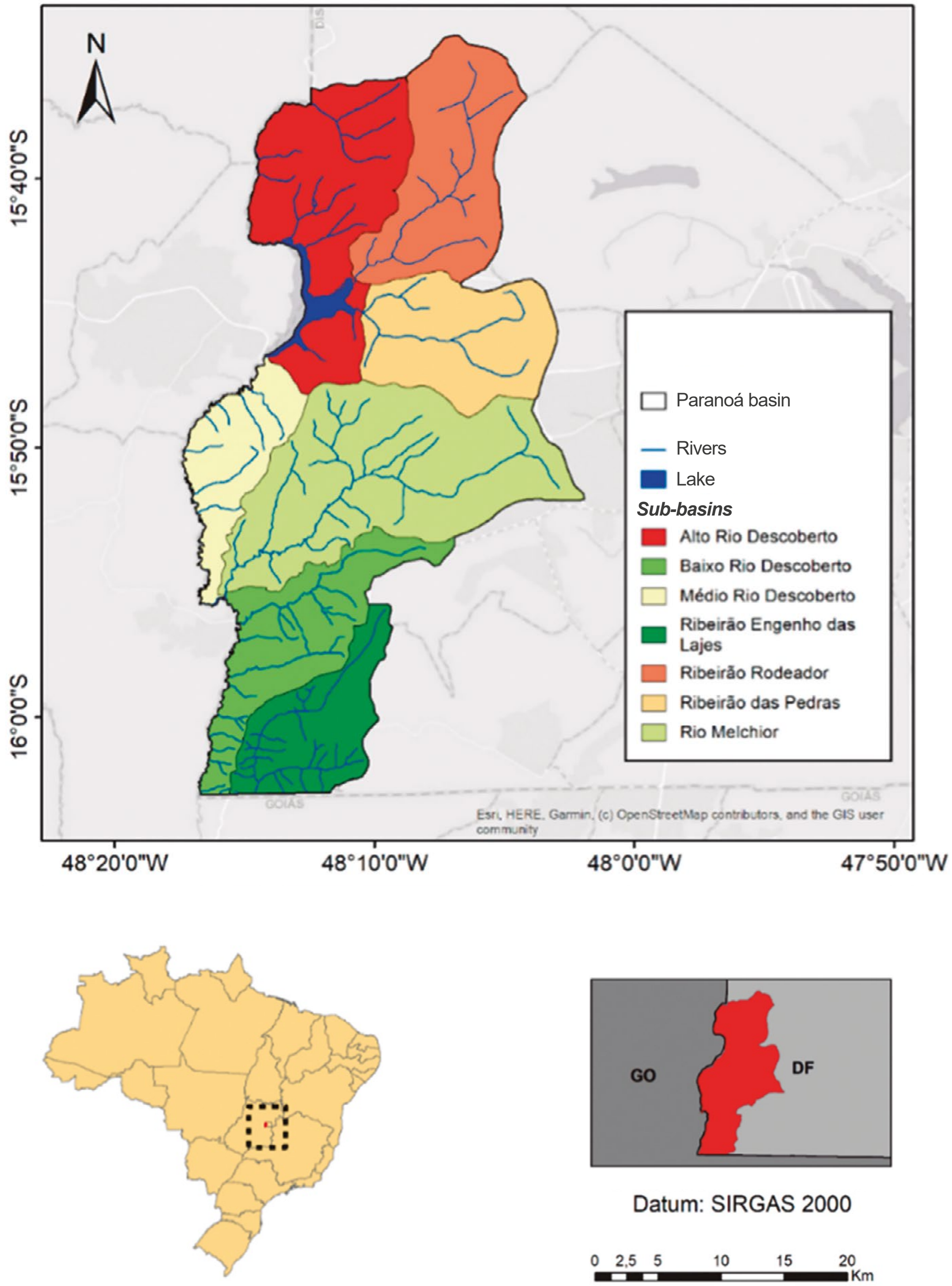
The Descoberto River Basin has, within the borders of the Federal District, a total area of 801 km^2(Figure 2.2). It has a gently undulating topography, with Oxisols dominating the landscape, and agriculture and native cerrado as dominant land uses.

The average annual precipitation in the Basin is 1,400 mm and the average inflow to its reservoir is 8 m^3/s. The Descoberto lake has a drainage area of 431 km^2 and an active volume of 86 hm^3, providing a guaranteed water supply of 5.2 m^3/s, which is enough for 1.7 million people. The Descoberto Basin is also an important vegetable and fruit producing area, which relies heavily on irrigation.

The specific water demand in the Descoberto Basin is high (6,000 inhab/hm^3) (FALKENMARK; WIDSTRAND 1992). In 2017, the Descoberto reservoir suffered significant depletion, even while operating below its design outflow.

The cause of the abrupt depletion of the reservoir, which reached 5% of its active volume at the end of 2017, was the sequence of six consecutive years of historical below-average precipitation, which generated a hydrological persistence (CHAVES; LORENA, 2019).

FIGURE 2.2 – DESCOBERTO RIVER BASIN



Source: Geoportal/DF

In the Descoberto River Basin, the Water Sustainability (WRSD) and Basin Sustainability (WSI) indexes were both applied to the present scenario (2015-2018).

Ribeirão Rodeador Basin

The Rodeador Basin is a sub-basin of the Descoberto River (Figure 2.2) with a total area of 113 km^2. This basin has an average annual rainfall of 1,417 mm, flat to gently undulating topography, with dominant Oxisols, and where irrigated and rainfed agriculture predominate as land use.

Although unregulated, the Rodeador river is one of the largest water contributors to the downstream Descoberto reservoir, with an average long-term annual flow of 1.7 m^3/s. The water demand in the Rodeador Basin, considering surface and underground sources, is 22 hm^3/year (Unesco, 2017).

As the Rodeador Basin was selected as the pilot basin in the present study, the water sustainability index (WRSD) and the water risk index (WRI) were applied to it for the present and future scenarios (2040 and 2070).

SUSTAINABILITY AND WATER RISK INDEXES

In the present analysis, a water sustainability index, a basin sustainability index, and a water risk index – the latter having been especially developed for this study – were applied to the selected basins.

The first two indexes were selected from the international literature, using previously established criteria and taking into account the objectives of the study; the hydrological, environmental and socioeconomic conditions of the basins studied; the availability of data; index robustness and ease of use; as well as these indexes' transparency and replicability.

Based on the above-mentioned criteria, the Water Resources System Dynamics - WRSD (XU et al., 2002) and the Watershed Sustainability Index - WSI (CHAVES; ALÍPAZ, 2007) were selected, both published in the international journal Water Resources Management (Springer).

During a Technical Workshop, held in July 2019 at the SEMA-DF headquarters (Figure 2.3), the pre-selected indexes were presented to managers and representatives of the civil society of the Federal District. Several suggestions for adjustments were presented and incorporated into the study.

FIGURE 2.3 – WORKSHOP ON SUSTAINABILITY AND WATER RISK HELD IN JULY 2019

Source: authors' elaboration

Water Sustainability Index

Developed by Xu and collaborators, the WRSD index assesses the performance of water systems based on the degree to which water supply is compromised by demand in watersheds. Thus, the WRSD balances the average water supply and demand (XU *et al.*, 2002):

$$WRSD = \frac{(0 - S)}{0} \quad \text{if } S > D \qquad [2.1]$$
$$WRSD = \text{zero} \quad \text{if } S \leq D$$

Where:

WRSD (0-1) = basin WRSD index;

D (hm^3/year) = average annual water demand in the basin; and

S (hm^3/year) = average annual water supply in the basin.

Once the WRSD had been calculated using equation 2.1, the inter-annual water sustainability was classified according to Table 2.1. More details about the WRSD index can be found in Xu et al (2002).

TABLE 2.1 – CLASSIFICATION OF INTER-ANNUAL WATER SUSTAINABILITY USING THE WRSD INDEX

VARIABLE	WRSD ≥ 0,8	0,2 < WRSD < 0,8	WRSD ≤ 0,2
Water Sustainability	High	Medium	Low

Source: Xu *et al.* (2002)

Watershed Sustainability Index

In the index developed by Chaves and Alípaz (2007), the integrated watershed sustainability is found using the arithmetic mean of the scores obtained in the four lines and three columns of a spreadsheet, where the indicators are the lines (H, E, L, P), and the columns are the basin Pressure, State, and Response (Table 2.2).

METHODOLOGY

TABLE 2.2 – WSI INDICATORS AND PARAMETERS

INDICATOR	PRESSURE	STATE	RESPONSE
Hydrology (H)	Variation in unit water demand (Da) during the period analyzed	Long-term unit water demand (Da) in the basin	Evolution in the efficiency of water use in the basin, during the period
	Change in total "P" during the period	Basin WQI (long term)	Variation in the WQI of the basin during the period
Environment (E)	Basin Environmental Pressure Index (EPI) during the period	% of natural vegetation in the basin	Evolution in the % of protected areas in the basin during the period
Livelihood (L)	Variation in the basin HDI-Income during the period	Basin weighted average HDI	Evolution of the basin's HDI during the period
Policy (P)	Variation in the basin HDI-Ed during the period	Legal and institutional capacity of the basin	Evolution on IWRM costs in the basin during the period

Source: adapted from Chaves and Alípaz (2007)

A The complete WSI matrix, with parameter values and scores, is displayed in the Appendix. The small adaptations made in the WSI in order to adapt it to the conditions of the Paranoá and Descoberto Basins were made to the *Hydrology-Quality indicator*. This adaptation was proposed during the CITinova Project Workshop, in 2019.

Hence, the original biochemical oxygen demand parameter – BOD was replaced by the basin total phosphorus and by the Water Quality Index- WQI. This replacement was envisioned in Chaves and Alípaz (2007), depending on local conditions.

Once the scores for H, E, L and P indicators were obtained, as well as Pressure, State and Response scores (see Appendix), the integrated watershed sustainability, during the period studied, was calculated using the equation (CHAVES; ALEPIZ, 2007):

$$WSI = \frac{H + E + L + P}{4} \qquad [2.2]$$

Where:

H (0-1) = hydrology indicator;

E (0-1) = environment indicator;

L (0-1) = livelihood indicator; and

P (0-1) = policy or governance indicator

As a consequence of the arithmetic mean of equation 2.2, both the indicators and the WSI index vary between 0 and 1. Similar to the WRSD index, the integrated sustainability calculated using the WSI is classified into three ranges (Table 2.3):

TABLE 2.3 – WATERSHED SUSTAINABILITY INDEX CLASSES

WSI VALUE	< 0,5	0,5 - 0,8	> 0,8
Integrated Sustainability	Low	Medium	High

Source: Chaves e Alipaz (2007)

In addition to the global watershed sustainability, given by equation 2.2, and its respective classes (Table 2.3), it is possible to identify in Table A1 (Appendix) the individual bottlenecks (score parameters ≤ 0.5) that affect the sustainability, allowing limiting factors to be mitigated. Further details on the WSI index can be found in Chaves and Alípaz (2007).

Finally, the integrated sustainability of the Descoberto and Paranoá Basins, calculated using the WSI, were compared to the sustainability of the other Latin American and Brazilian basins, calculated using the same index.

Water Risk Index

To assess the *intra-annual* water risk of the Ribeirão Rodeador Pilot Basin, considering the dynamic aspects of water supply and demand during the dry and rainy periods of the year, a computational risk model was developed to complement the *inter-annual* water sustainability analysis, estimated by the WRSD index.

Taking probability of failure as the risk indicator of a given system, represented by the watershed, the risk is given by (HARR; 1987):

$$R = p_f = P\,(C < D) \qquad [2.3]$$

Where:

R = risk of system failure;
P = probability function;
C = system capacity; and
D = demand on the system.

In turn, taking water supply (S) as the system capacity and the water demand (D) as the system demand, and knowing that these are random variables, with distributions and cross-correlation, their distributions and variance-covariance matrix must be calculated to estimate the risk "R".

Considering safety margin (M_s) as the difference between water supply and demand, we have that M_s = S – D (GANOULIS, 2009). Thus, the *water risk*, given by the probability of supply failure in the basin, will be the probability of Ms being equal to or less than zero, that is:

$$R = p_f = P\,(M_s \leq 0) \qquad [2.4]$$

Where:

M_s = safety margin (S – D) of the system (basin).

By dividing the expected average of the safety margin by its standard deviation, we find the System Reliability Index (I_r) (HARR, 1987):

$$I_r = E[M_s] / s[M_s] \qquad [2.5]$$

Where:

I_r = system reliability index;

$E[M_s]$ = average safety margin;

$s[M_s]$ = safety margin standard deviation.

Since the safety margin of a water system is the difference between average supply and demand, the coefficient of variation of the safety margin is given by the following equation (MCCUEN; SNYDER, 1986):

$$V[M_s] = V[S - D] = V[S] + V[D] - 2\,r\,s[S]\,s[D] \qquad [2.6]$$

Where:

$V[M_s]$ = coefficient of variation of the system's safety margin;

$V[S]$ = coefficient of supply variation;

$V[D]$ = coefficient of demand variation;

r = correlation coefficient between supply and demand;

$s[S]$ = standard deviation of supply; and

$s[D]$ = standard deviation of demand.

Recognizing that equation 2.5 is the reciprocal of the coefficient of variation of the system's safety margin, we have:

$$V[M_s] = s[M_s] / E[M_s] \qquad [2.7]$$

Where:

$V[M_s]$ = coefficient of variation of the system's safety margin.

Considering that equation 2.7 is the complement of the probability of failure (equation 2.4), the water risk index is the reciprocal of equation 2.7, i.e.:

$$WRI = p_f = 1 - \psi\left[\frac{E[O] - E[D]}{\sqrt{s^2[S] + s^2[D] - 2\, r\, s[S]\, s[D]}}\right] \qquad [2.8]$$

Where:

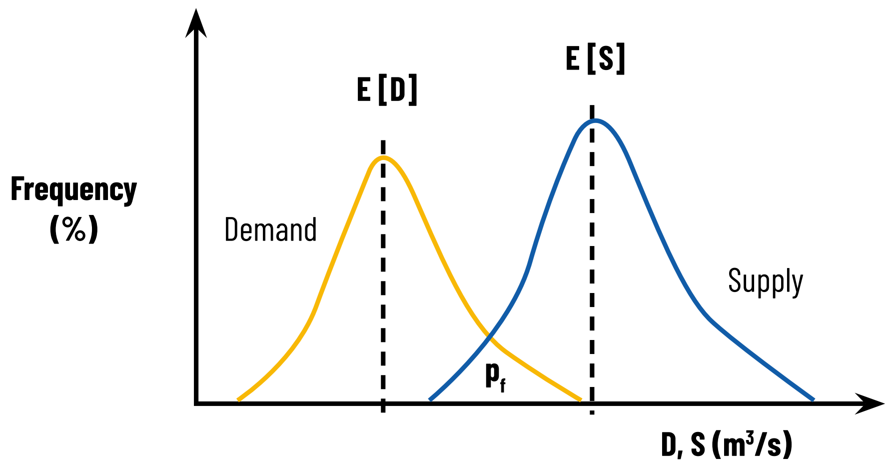
WRI = water risk index, estimated by the probability of failure, p_f;
E[O] = average monthly water supply;
E[D] = average monthly water demand;
s[O] = standard deviation of supply;
s[D] = standard deviation of demand;
r = correlation coefficient between supply and demand;
$\Psi[\cdot]$ = the value of the normal distribution function, obtained through the MS-Excel NORM.S.DIST() function.

In equation 2.8, the operator $\Psi[\cdot]$ requires that the distributions of water supply and demand be normal. To test their normality, the Kolmogorov-Smirnov test was used (HAAN, 1994).

Thus, knowing the distributions of the average monthly water supply and demand in the basin, and their correlation, the probability of system failure is found, which is an unbiased estimator of the intra-annual water risk.

Graphically, the probability of failure (p_f), taken here as the Water Risk Index – WRI, is represented by the tail overlap area of the water supply (S) and demand (D) distributions, indicating the probability of water demand being greater than supply, which are both random variables (Figure 2.4).

FIGURE 2.4 – GRAPHIC REPRESENTATION OF THE PROBABILITY OF FAILURE (p_f), BASED ON WATER SUPPLY (S) AND DEMAND (D) DISTRIBUTIONS IN THE BASIN



Source: authors own elaboration own elaboration

Thus, equation 2.8, graphically represented by Figure 2.4, was used to estimate the intra-annual water risk in the Rodeador Basin, according to the basin's intra-annual water supply and demand. To facilitate the calculations above (WRI and KS normality test), they were entered into an MS-Excel macro spreadsheet (available upon request).

DATA SOURCES & COMPILATION

Since the WSI and WRSD demand local secondary data – including data on hydrology, the environment, socio-economics and governance aspects – these were collected, whenever possible, from official databases.

Both the Descoberto and Paranoá Basins met the WSI size criteria, i.e., A < 2,500 km^2 (CHAVES; ALÍPAZ, 2007). Their areas are 801 km^2 and 1,056 km^2, respectively. In the case of the WRSD, there is no criterion regarding basin minimum or maximum area (XU et al., 2002).

With regard to *hydrologic information*, sream flow data from existing gauging stations in the basins were used, as well as water quality data. The database included the HDIroweb (http://www.snirh.gov.br/hidroweb/publico/medicoes_historicas_abas.jsf), of the National Water and Basic Sanitation Agency of the Federal District (*ANA*), as well as data supplied by the Water, Energy and Sanitation Regulatory Agency of the Federal District (*ADASA*) and the Environmental Sanitation Company of the Federal District (*Caesb*).

Regarding *socioeconomic data*, these were obtained from the Brazilian Institute of Geography and Statistics - IBGE, from the National Household Sample Survey - PNAD, from the Planning Company of the Federal District – Codeplan, and from the United Nations Development Program – UNDP.

The *environmental information* (remaining natural areas, Conservation Units, parks etc.) was obtained from the database of the State Secretariat for Urban Development and Housing of the Federal District - SEDUH-DF/GeoPortal (https://www.geoportal.seduh.df.gov.br/mapa/).

In turn, the data on water resources regulation and management, laws, resolutions, water use permits (surface and underground), Ecological-Economic Zoning - ZEE, water resources and basin plans were obtained from public records. Additionally, data on the perception of the effectiveness of water management in the basins studied were obtained from questionnaires and applied to managers and representatives of organized civil society.

The annual average precipitation (P) and temperature (T) projections for different future scenarios of GHG emissions were obtained from the study prepared by CPTEC-INPE (2019), spanning the Federal District and surrounding areas (RIDE areas). The climate projections were generated through the HadGEM2/Eta model, on a 5x5 km grid. Table 2.4 presents the data used in this study, with the respective sources and activities.

TABLE 2.4 – DSECONDARY DATA USED IN THIS ANALYSIS, WITH THE RESPECTIVE SOURCE AND ACTIVITY

DATA	SOURCE	ACTIVITY
Flow	ANA, ADASA, CAESB	Estimate the supply and demand for water in the two basins
Water Quality	ANA, ADASA, CAESB	Estimate the quality of water in the watercourses of the two basins
Population	Codeplan, Censo	Estimate per capita water supply and human pressure indicators
Land use and Conservation Units	Codeplan, Brasília Environmental	Estimate the degree of environmental protection and anthropogenic pressure in the basins
HDI	Pnud, Codeplan	Estimate the degree of human development of the different Administrative Regions of the two basins
Public policies on the Water Resources Management (IWRM)	ANA, SEMA DF, ADASA, CAESB, Brasília Environmental, UGP-Descoberto, CITinova	Survey the main public policies in the IWRM sector existing in the two basins studied
P and T in future scenarios	CPTEC-INPE (2019)	Obtaining future water supplies in the Rodeador Basin, in different GHG emission scenarios, in the years 2040 and 2070

Source: authors' elaboration

SCENARIOS USED IN THE ANALYSIS

For the case of the WSI and WRSD index of the Descoberto and Paranoá Basins, the sustainability was calculated considering the current scenario of climate, water availability, land use and public policies.

As for the WSI index, applied to the Paranoá and Descoberto Basins, the *current scenario* included a period of four years (from 2015 to 2018), as recommended by Chaves and Alípaz (2007). For the WRSD index, applied to the Descoberto, Paranoá and Rodeador Basins, the current scenario of water supply considered the period between 1999 and 2018. The water demand was taken as of 2017 (UNESCO, 2017).

In the case of pilot Rodeador Basin, distinct climate and water demand scenarios, present and future, were used for the WRSD and WRI indexes. These scenarios are presented below.

Water Supply Scenarios

In the case of the WRSD in the Descoberto and Paranoá river basins, the water supply in the current scenario considered the time series of annual inflow volumes (1999-2018) which were added to the regulating volumes of their respective reservoirs (CHAVES; LORENA; 2019). The water demand considered was the basins' licensed water volumes of surface and groundwater sources, in 2017 (UNESCO, 2017).

For the WSI index, the current scenario of water supply and of socioeconomic, governance and environmental indicators considered the period between 2015 and 2018. In the case of the WRI index, the current scenario of intra-annual water supply used the historical series of natural flows that were reconstituted, during the period between 1999-2018 (20 years). The water demand considered, in turn, was the licensed water volumes in the basin, in 2017. The periods used in the present scenarios of the WSI, WRSD and WRI indexes are shown in Table 2.5.

TABLE 2.5 – PRESENT SCENARIOS FOR THE WSI, WRSD AND WRI INDEXES IN THE PARANOÁ, DESCOBERTO AND RODEADOR BASINS

INDEX	SUPPLY	DEMAND
WSI	1999-2018/2015-2018	2015-2018
WRSD	1999-2018	2017
WRI	1999-2018	2017

Source: authors' elaboration

The future water supply scenarios of the WRSD and WRI indexes in the Rodeador Basin used annual temperature (T) and precipitation (P) projections, which were estimated using the HadGEM2 (GCM) model and the Eta-RCM model (INPE, 2019), on grid cells of 5x5 km. Distinct IPCC greenhouse gas emissions scenarios were used in the years 2040 and 2070 (Table 2.6 and Figure 2.5).

TABLE 2.6 – CLIMATIC SCENARIOS FOR ESTIMATING WATER SUPPLY IN THE RODEADOR BASIN, IN ORDER TO APPLY THE WRSD AND WRI INDEXES

CLIMATE SCENARIO	PRESENT	BAU	PESSIMISTIC
Variables	P & T anual	P & T anual	P & T anual
IPCC Code	-	RCP 4.5	RCP 8.5
Scenario Description	Current	4,5 W/m^2 radiative forcing	8 W/m^2 radiative forcing
Period	1999-2018	2040 and 2070	2040 and 2070

Source: authors' elaboration

In the present scenario, the water supply in the Rodeador Basin was taken as the long-term average annual flow (1999-2018) at its outlet, after the reconstitution of the natural flows (OLIVEIRA et al., 2008), removing the consumptive flow bias, i.e.:

$$Q_n = Q_o + Q_c \qquad [2.9]$$

Where:

Q_n (m^3/s) = reconstituted natural flow;

Q_o (m^3/s) = observed flow; and

Q_c (m^3/s) = consumptive flow.

For future scenarios, the water supply in the Rodeador Basin was calculated through simulations with the Gardner's (2009) model, using the annual P and T projections of the HadGEM2/Eta model for 2040 and 2070. Hence, the specific average annual flow in the Roedador Basin was calculated through the following equation (GARDNER; 2009):

$$Q_e = P \cdot e^{(-ET/P)} \qquad [2.10]$$

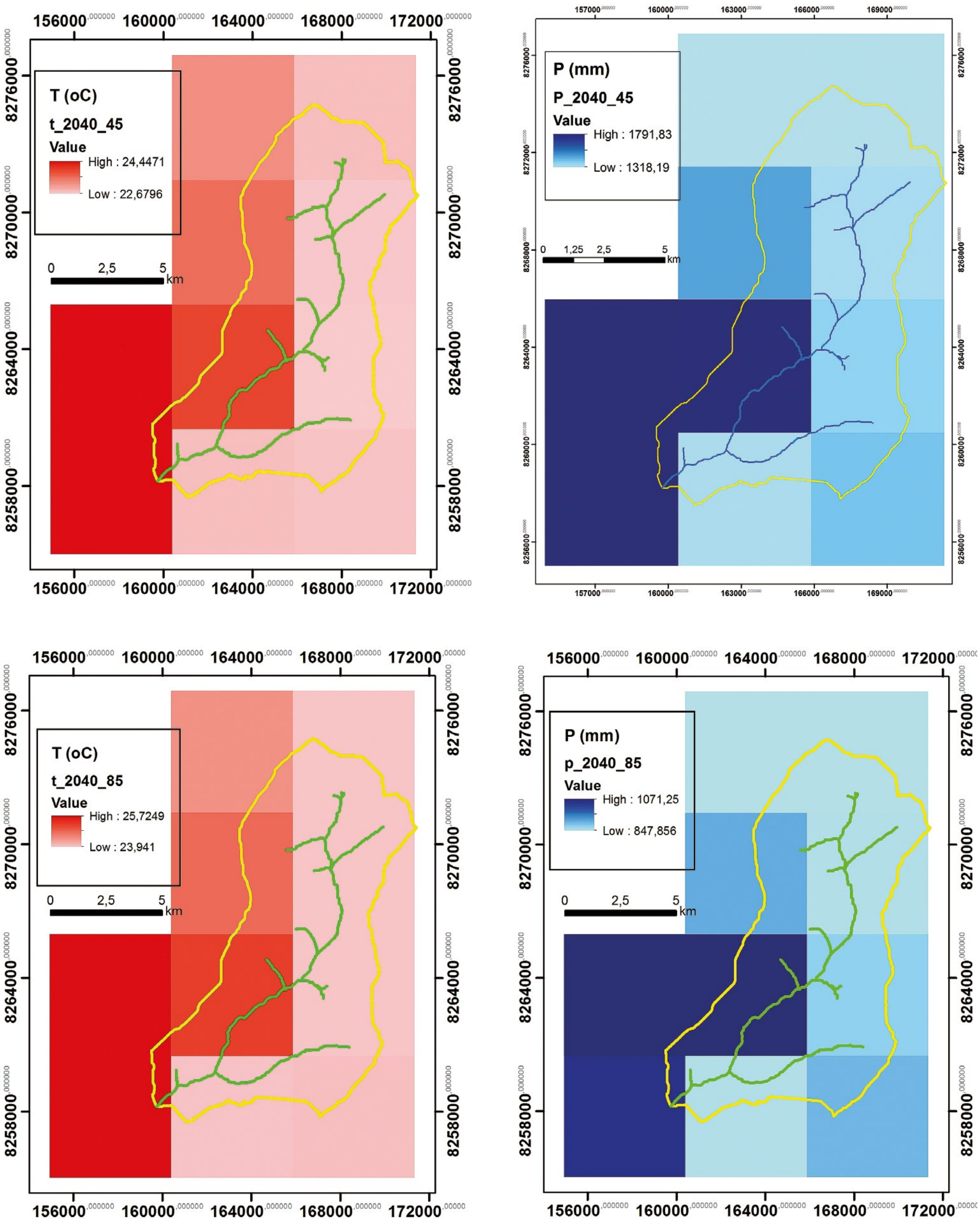
Where:

Q_e (mm) = average annual runoff;

P (mm) = average annual precipitation in the basin; and

ET (mm) = average annual potential evapotranspiration in the basin.

FIGURE 2.5 – TEMPERATURE (T) AND PRECIPITATION (P) PROJECTIONS OF THE HADGEM2/ETA MODEL FOR 2040 IN THE RODEADOR BASIN IN DIFFERENT FUTURE GHG EMISSION SCENARIOS



Source: authors' elaboration

The annual ET value in the Rodeador pilot basin, for the future scenarios, was calculated through Holland's equation (1978):

$$ET = 1{,}2 \, . \, 10^{10} \, e^{(-4620/Tk)} \qquad [2.11]$$

Where:

ET (mm) = average annual potential evapotranspiration in the basin;

T_k (º Kelvin) = average annual basin temperature ($T_{Kelvin} = T_{Celcius} + 273.2$).

As it is a Budyko-type model, equation 2.10 does not require prior calibration (GARDNER; 2009). However, it was ratified for the Rodeador Basin by using the historical series of P, T and Q, yielding a relative error of 5%, considered acceptable.

Water Demand Scenarios

In the case of the WSI index, the current water demand scenario was based on the average water consumption in the administrative regions of the Federal District, which are served by the sources of the Descoberto and Paranoá Basins, during the period between 2015 and 2018.

For the WRSD index, the current water demand for the three Basins studied was taken as the sum of the surface licensed water and half of the licensed groundwater in 2017. This was due to the fact that the base flow of the river is partially captured by pumping tube wells in the basins (USGS, 2012), mainly in those which have dominant porous systems, such as the Rodeador Basin.

In the 2040 and 2070 scenarios, water demand in the Rodeador Basin were based on projections of the water demand evolution in the Basin in 2026 (UNESCO, 2017).

RESULTS & RECOMMENDATIONS

Descorberto, Paranoá and Rodeador Basins were classified as *high*, *medium* and *low*, respectively. Additionally, the bottlenecks that contributed to the reduction of the indexes' scores were identified, and appropriate recommendations were made to increase water and integrated sustainability, as well as to reduce water risk.

COMPARISONS WITH OTHER BASINS

In order to assess the degree of water and integrated sustainability of the basins analysed, the results obtained were compared with those of other Latin American basins.

Furthermore, the results of the WRSD and WRI indexes, calculated for the present scenario in the Rodeador pilot basin were compared with those of the future climate scenarios (RCP 4.5 and 8.5), in 2040 and 2070.

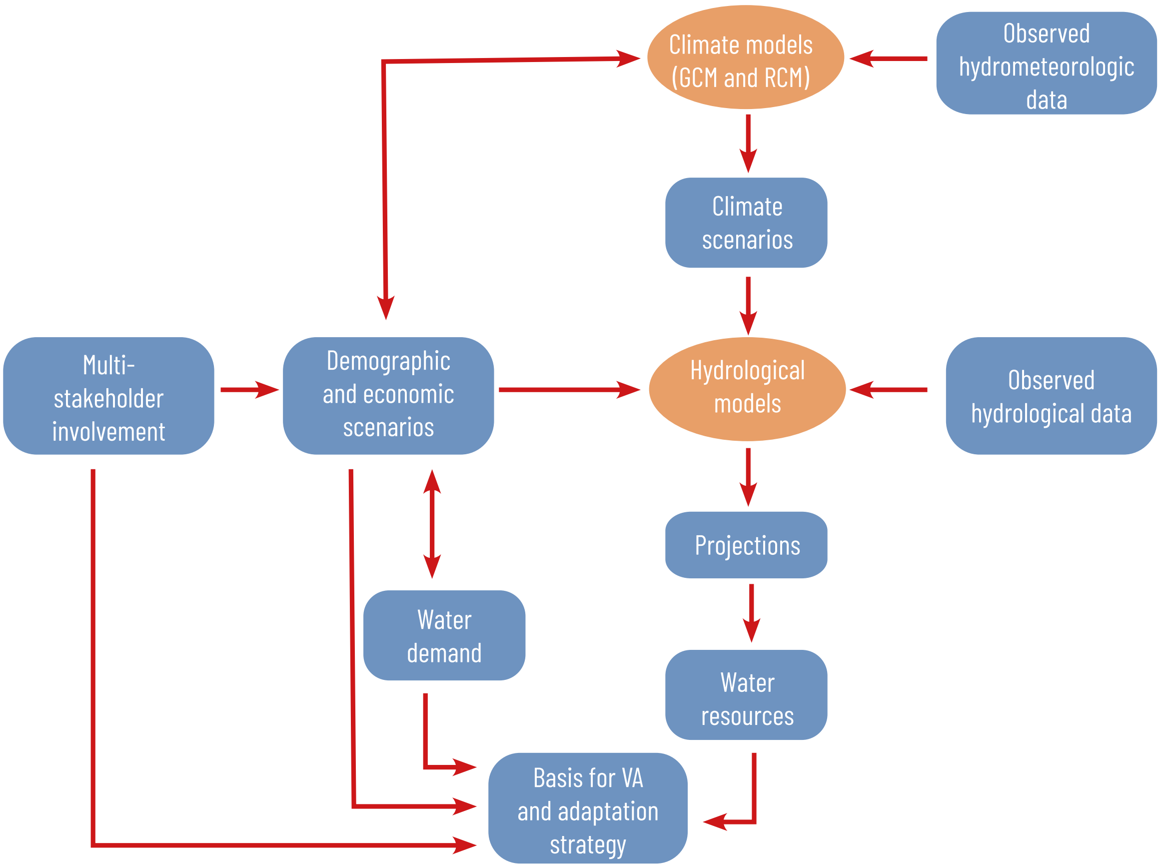
UNCERTAINTIES ASSOCIATED WITH SUSTAINABILITY & WATER RISK

As was the case of the indexes, the data used and future projections have different degrees of uncertainty. Thus, both cases were analyzed, as well as the uncertainty in the results obtained, in order to guide the decision-making process.

ADAPTATION STRATEGIES TO FUTURE THREATS

Once the impacts of climate change and water demand affecting sustainability and water risk were evaluated for the pilot basin, adaptation measures were proposed following the guidelines of the European Union (Figure 2.6).

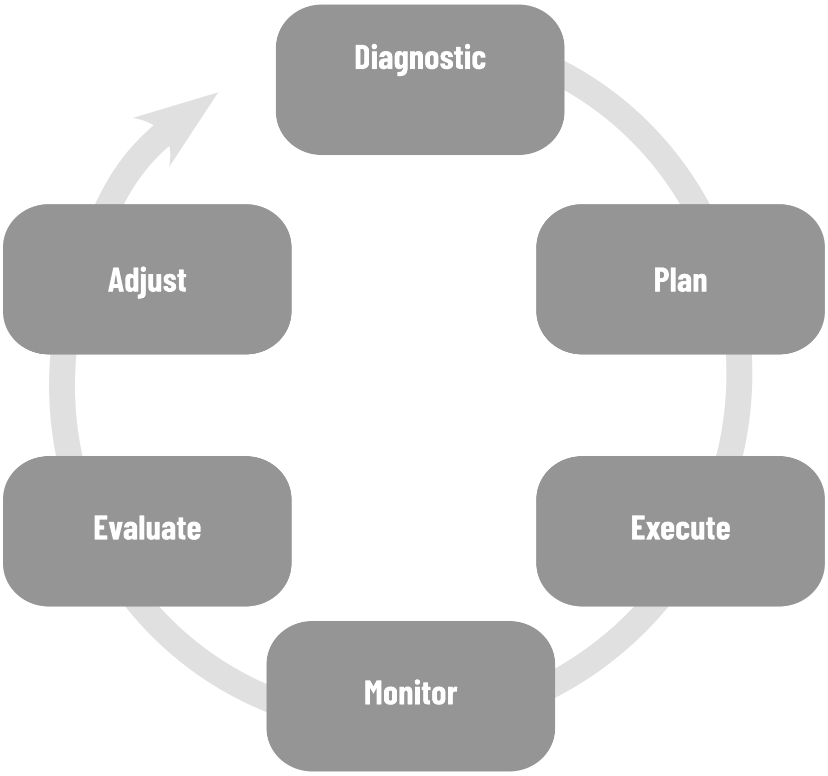
FIGURE 2.6 – WATER VULNERABILITY ANALYSIS PROCESS AND ADAPTATION STRATEGY



Source: adapted from ECE (2009)

Adaptation measures include different legal, regulatory, economic, governance and educational instruments, always following the adaptive management process (Figure 2.7).

FIGURE 2.7 – WATERSHED ADAPTIVE MANAGEMENT CYCLE



Source: authors' elaboration

3 RESULTS

INTEGRATED SUSTAINABILITY OF BASINS

The integrated sustainability of the Descoberto and Paranoá Basins, calculated through the WSI in the present scenario (2015-2018), was found using equation 2.2, and corresponding look-up tables. The results of the integrated sustainability of the two basins are presented below.

Descoberto Basin

Hydrology Indicator (H)

The hydrology indicator is made up of the sub-indicators of water quantity and quality (rows of Table 2.2). The latter, in turn, are formed by the depression, state and response parameters (columns of Table 2.2), in a total of six parameters.

Hydrology-Quantity

The water supply in the Upper Descoberto River Basin upstream of the dam, taken as the area for estimating water availability, was based on the series of annual affluent volumes to the reservoir between 1999 and 2018 using data from the different river gauge stations of its tributaries, including the incremental areas of the basin.

In the period between 1999 and 2018, the long-term average annual inflow volume was 233.7 hm^3/year. In the base period (2015-2018), the average annual affluent volume was 150.2 hm^3/year. Considering that the flow regulation capacity of the Descoberto reservoir is 54.9 hm^3 (see Figure 1.1), corresponding to 76% of its active volume. The latter figure was added to the average inflow in the two periods analyzed, to obtain the basin water supply, i.e., 233.7+54.9 = 288.6 hm^3/year (1999-2018), and 150.2+54.9 = 205 ,1 hm^3/year (2015-18).

In terms of water demand, the population supplied by the Descoberto Basin numbered 1,717,405 inhabitants in 2018, with 376,212 water connections, spanning 13 Administrative Regions of the Federal District.

Considering that the basin unit water demand (D_a) is the ratio between the population and the water supply in the Basin (CHAVES; ALÍPAZ 2007), this parameter, in the two periods analyzed, was simply:

$$D_a = 1{,}717{,}405 / (233.7+54.9) = 5{,}951 \text{ hab/hm}^3\text{.yr} \quad (1999\text{-}2018)$$

$$D_a = 1{,}717{,}405 / (150.2+54.9) = 8{,}374 \text{ hab/hm}^3\text{.yr} \quad (2015\text{-}2018)$$

Table 3.1 presents D_a results for the two periods and the respective basin Hydrology-Quantity-State parameter score.

RESULTS

TABLE 3.1 – AVERAGE UNIT WATER DEMAND (D_a) IN THE DESCOBERTO BASIN, IN THE TWO PERIODS ANALYZED AND RESPECTIVE HYDROLOGY-QUANTITY-STATE PARAMETER SCORE

PERIOD	1999-2018	2015-2018	ESCORE
D_a (hab./hm^3.ano)	5,951	8,374	0.0

Source: authors' elaboration

According to Table 3.1, the basin score corresponding to the Hydrology-Quantity/State parameter was zero (0). This is due to the fact that, when it exceeds 2,000 inhab/hm^3.year, the basin is water-stressed (FALKENMARK; WIDSTRAND 1992).

In the case of the WSI Hydrology-Quantity/Pressure parameter, the unit water demand between 2015 and 2018 was 8,890 inhab/hm^3.yr, and its variation in the period was (CHAVES; ALÍPAZ 2007):

$$\Delta \, Da = 100 \; \frac{Da_{\,2015-2018} - Da_{\,1999-2018}}{Da_{\,1999-2018}} \qquad [3.1]$$

Where:

ΔDa = percentage of unit water demand variation in the study period;

$Da_{1999-2018}$(hab./hm^3.yr) = long-term average unit water demand; and

$Da_{2015-2018}$(hab./hm^3.yr) = average unit water demand in the period 2015-18.

For the Descoberto Basin, the relative variation in per capita demand (ΔDa) was +40.7%, which corrensponds to a score of 0 (zero) in the WSI. As the value of 2,000 inhab/hm^3.year was surpassed, both long-term unit demand (1999-2018) and short-term variation (2015-2018) indicate a situation of potential water stress (FALKENMARK; WIDSTRAND 1992).

This water stress happened in 2017, when the unit demand exceeded 8,000 inhab/hm3.year, requiring a 30% reduction in the reservoir abstractions and leading to a water rationing process that affected1,8 million inhabitants.

Finally, the Hydrology-Quantity/Response parameter analyzed the evolution of the water use efficiency in the basin for the present period (2015-18). In order to reduce the estimation bias of this parameter, questionnaires were distributed to water managers and stakeholders (Table 3.2).

TABLE 3.2 – QUESTIONNAIRE DISTRIBUTED TO MANAGERS AND STAKEHOLDERS TO ASSESS THE BASIN HYDROLOGY-QUANTITY-RESPONSE PARAMETER

CRITERION	LEVEL	ESCORE
Efficiency increased by more than 20%, with lasting measures	Very good	1.00
Efficiency increased by more than 20%, with temporary measures	Good	0.75
Efficiency increased by more than 10%, with temporary measures	Medium	0.50
Water use efficiency had no increase or has decreased	Poor	0.25
Water use efficiency decreased	Very poor	0.00

Source: authors' elaboration

Additionally, the following management responses were made for water stress mitigation in the Basin during the water crisis, among these are:

- Establishing of a 25% water rationing in all administrative regions supplied by the basin;
- Interconnecting the Descoberto and the Santa Maria/Torto Systems, increasing the efficiency of the water macro-allocation;
- Levying contingency tariffs from water users and consumers during the water crisis; and its application in mitigating actitivies;
- Conducting public awareness campaigns on the importance of saving water;
- Imposing restrictions on irrigation water use in the basin, allowing a water surplus for urban water users.

The above-mentioned measures allowed for a significant reduction in the water abstraction from the Descoberto reservoir during the water crisis, from 5.2 m^3/s to 3.5 m^3/s, which was followed by an increase in water use-efficiency. Although positive, this increase in water-use efficiency had two drawbacks: i) Many of the measures adopted were temporary rather than permanent; ii) Irrigation suffered a significant water-use restriction, without the adequate compensation.

As a consequence, a mean value was assigned to the Hydrology-Quantity/Response parameter, corresponding to a score of 0.50.

Hydrology-Quality

The total phosphorus (P) and Water Quality Index (WQI) data, used to assess the Hydrology-Quality parameter, were obtained from the six main tributaries of the Descoberto reservoir, and also from the lake itself (Figure 3.1). The historical series of parameters comprised the period between 2001 and 2018.

FIGURE 3.1 – DESCOBERTO RESERVOIR

Source: Caesb

Thus, averages P and WQI were found for the periods between 2001 and 2018, and between 2015 and 2018. The relative change in P (and, similarly, in the WQI) between these two periods was found through:

$$\Delta P = 100 \frac{P_{2015-2018} - P_{2001-2018}}{P_{2005-2018}} \qquad [3.2]$$

Where:

ΔP (%) = change in average total phosphorus concentration between periods;

$P_{2015-2018}$ (mg/L) = average total phosphorus concentration in the period between 2015 and 2018;

$P_{2001-2018}$ (mg/L) = average total phosphorus concentration in the period between 2001 and 2018.

In the case of the Hydrology-Quality-Pressure parameter, Table 3.4 presents the average total phosphorus, measured with the main tributaries and with the Descoberto lake itself, in the two periods analyzed, as well as with the percentage change between both periods' averages.

TABLE 3.4 – AVERAGE TOTAL P IN THE DESCOBERTO BASIN, RELATIVE CHANGE AND CORRESPONDING SCORE FOR THE PARAMETER

PARAMETER	AVERAGE 2001-2018	AVERAGE 2015-2018	% CHANGE	ESCORE
P total (mg/L)	0.025	0.016	-38.5	1.00

Source: authors' elaboration

According to Table 3.4, there was a 38.5% reduction in total phosphorus levels in the Descoberto Basin between the two periods, corresponding (Table A1) to a score of 1.00 for the Hydrology-Quality-Pressure parameter. In the case of the WSI Hydrology-Quality-State parameter, Table 3.5 shows the average WQI parameter and the % change between the two periods analyzed.

TABLE 3.5 – VAVERAGE WQI VALUES FOR THE DESCOBERTO BASIN, FOR THE PERIOD STUDIED, % CHANGE AND CORRESPONDING SCORE FOR THE HYDROLOGY-QUALITY-STATE PARAMETER

PARAMETER	AVERAGE 2005-2018	AVERAGE 2015-2018	% CHANGE	ESCORE
WQI	74.4	69.0	-7.2	0.75

Source: authors' elaboration

The Hydrology-Quality-Response parameter was found through the WQI change in the Basin during the period studied (2015-2018). The 7.2% reduction in the WQI corresponds to a score of 0.75 in Table 3.6. Table 3.7 presents the synthesis of the H indicator for the Descoberto River Basin.

TABLE 3.6 – VALUES AND SCORES OF HYDROLOGY - QUALITY IN THE DESCOBERTO BASIN SUB-INDICATOR, DURING 2015-2018

HYDROLOGY -QUALITY	PRESSURE	STATE	RESPONSE
Value	-38.5%	74.4	-7.2%
Escore	1.00	0.75	0.75

Source: authors' elaboration

Considering that the hydrology indicator (H) of the WSI is the arithmetic mean of the values of the sub-indicators H-quantity and H-quality, Table 3.7 presents the synthesis of the indicator H in the Descoberto River Basin.

TABLE 3.7 – SYNTHESIS OF THE HYDROLOGY INDICATOR (H) OF THE DESCOBERTO BASIN

SUBINDICATOR	PARAMETER / SCORES			AVERAGE
	PRESSURE	STATE	RESPONSE	
H-Quantity	0.00	0.00	0.50	0.17
H-Quality	1.00	0.75	0.75	0.83
H (Hydrology)	0.50	0.38	0.63	**0.50**

Source: authors' elaboration

According to Table 3.7, the score of the Hydrology indicator in the Descoberto River Basin was 0.50, which is considered *medium*. The limiting factor in terms of sustainability was the basin's water availability, of which the score (0.17) was four times lower than that of water quality (0.83).

Environment Indicator (E)

In order to estimate the Environmental Indicator (E) in the Descoberto Basin, secondary information on land use and land cover of the Federal District, obtained from different official sources, was used, considering the period between 2015 and 2018. After compiling this information, they were analyzed to obtain the values and scores for the three parameters of the indicator.

The Pressure parameter of the WSI Environmental Indicator was calculated using the Environmental Pressure Index - EPI (CHAVES; ALÍPAZ, 2007):

$$EPI = \frac{\Delta Aa + \Delta Au}{2} \qquad [3.3]$$

Where:
EPI = basin environmental pressure index;
ΔAa (%) = % change in agricultural areas in the basin during the period of 2015-2018;
ΔAu (%) = % change in urban areas in the basin during the period of 2015-2018.

The agricultural and urban areas of the Descoberto River Basin were estimated through spatial analysis with the GIS, using state land-use maps from 2015 and 2018 (MapBiomas, 2019). In those maps, the land-use classes "pasture" and "crops" were considered agricultural areas.

The changes in agricultural and urban areas in the period and the respective EPI of the Descoberto Basin, are shown in Table 3.8. Since the basin EPI was negative (-0.15%), the score for the Environment-Pressure parameter was high (1.0).

FIGURE 3.2. LAND-USE IN THE DESCOBERTO RIVER BASIN IN 2015

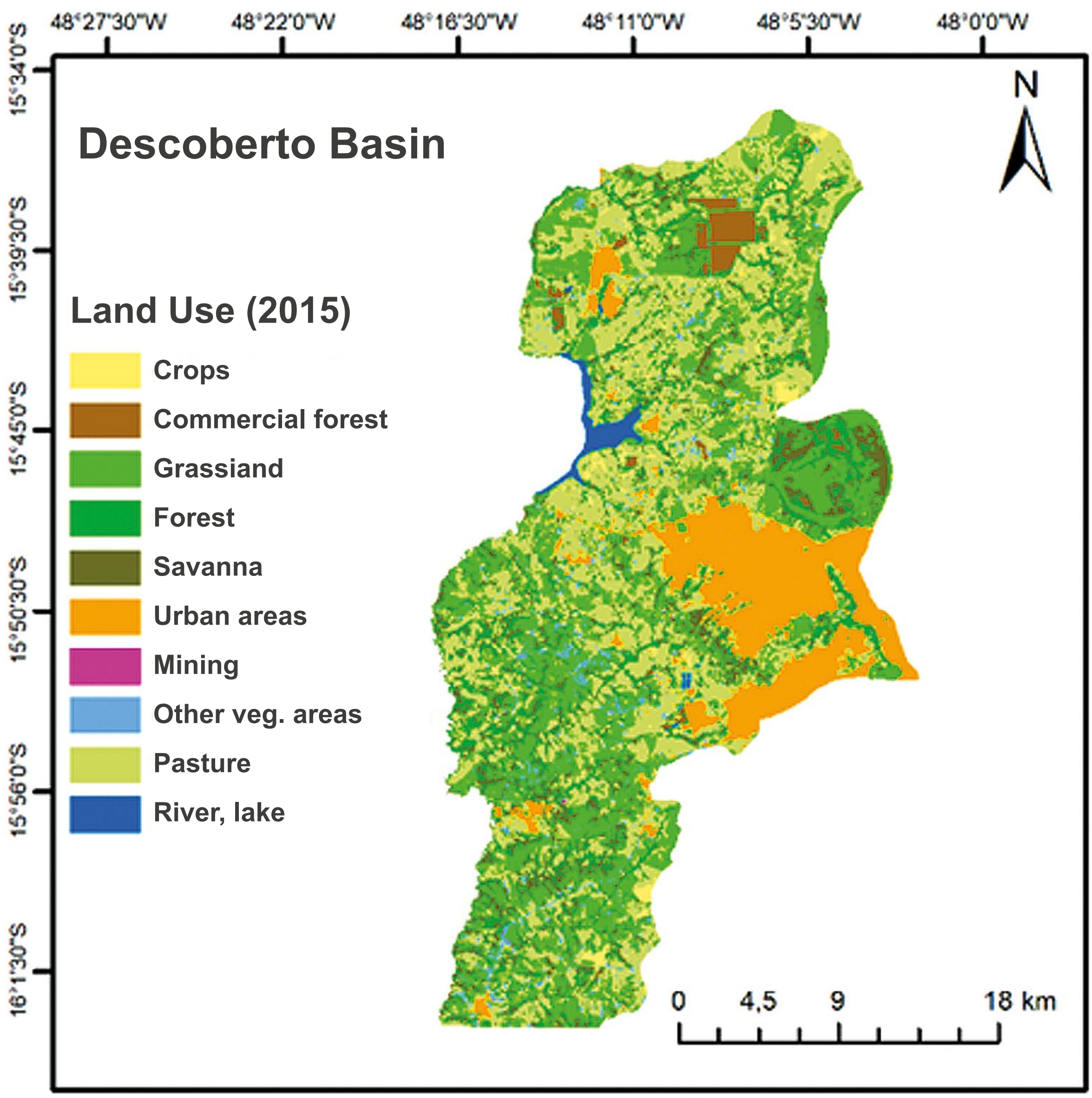


TABLE 3.8 – WSI VALUES AND SCORES FOR THE ENVIRONMENT-PRESSURE (EPI) PARAMETER IN THE DESCOBERTO BASIN

AGRICULTURAL AREAS (KM^2)			URBAN AREAS (KM^2)			EPI	ESCORE
2015	2018	% CHANGE	2015	2018	% CHANGE		
285.34	277.78	-3	102.11	104.52	2	-0.15%	1.00

Source: authors' elaboration

In 2018, native vegetation in the Descoberto Basin represented 384.13 km^2 (Table 3.9), corresponding to 47.9% of its total area. This value corresponds to a score of 1.00 for the Environment-State parameter, indicating a high percentage of conserved areas in the Basin.

TABLE 3.9 – PERCENTAGE OF NATIVE VEGETATION IN THE DESCOBERTO BASIN AND THE RESPECTIVE SCORE FOR THE ENVIRONMENT-STATE PARAMETER

LAND-COVER	AREA (KM^2)	% BASIN	ESCORE
Grassland	167.72	20.9	-
Savanna	129.10	16.1	-
Forest	87.30	10.9	-
Total	**384.13**	**47.9**	**1.00**

Source: authors' elaboration

As for the Environment-Response parameter of the WSI, the evolution in the effective protected areas (AP) in the Descoberto Basin was calculated during the period studied (2015-18). To this end, data on existing federal and district Conservation Units (CUs) in the Basin were collected (MMA, 2019; GEOPORTAL, 2019) and analyzed with the GIS.

Data on the land-use change of these conservation areas was obtained through the superposition of their land-use classes during 2015 and during 2018. The relative change of the conserved/managed areas between 2015 -2018 was calculated through:

$$EAP = 100 \frac{AP_{2018} - AP_{2015}}{AP_{2015}} \qquad [3.4]$$

Where:

EAP (%) = % change in the protected or managed areas in the period;

AP_{2015}(ha) = sum of forest, savanna and grassland areas in 2015;

AP_{2018}(ha) = sum of forest, savanna and grassland areas in 2018.

In the Descoberto Basin, 19 federal and district parks and conservation units were identified, with a total of 866.3 ha, all established before 2015.

To obtain the % change of the protected areas in the Basin between 2015 and 2018, the variation in land-use in these CUs during the period was compared. The Environmental Protection Areas - APAs and Areas of Relevant Ecological Interest - *ARIEs* were not included in the analysis.

Between 2015 and 2018, an increase of 10% and 23% in forest and savanna areas, respectively, was observed in the basin's CUs. However, there was a 13% reduction in the grassland area. In net terms, there was a relative increase of 2.3% in natural areas within the Basin CUs. This increase corresponded to a score of 0.5 according to the parameter.

TABLE 3.10 – % CHANGE IN NATIVE VEGETATION IN PARKS AND CONSERVATION UNITS IN THE DESCOBERTO RIVER BASIN BETWEEN 2015 AND 2018

YEAR	NATURAL AREAS (KM^2)	ESCORE
2015	69.42	-
2018	71.03	-
Variation	**2.3%**	**0.50**

Source: authors' elaboration

Table 3.11 presents the synthesis of the Environment indicator (E) of the Descoberto River Basin. In this Table, the value of the Environment indicator was 0.83, which classifies as *high*.

TABLE 3.11 – SYNTHESIS OF THE ENVIRONMENT INDICATOR (E) FOR THE DESCOBERTO RIVER BASIN

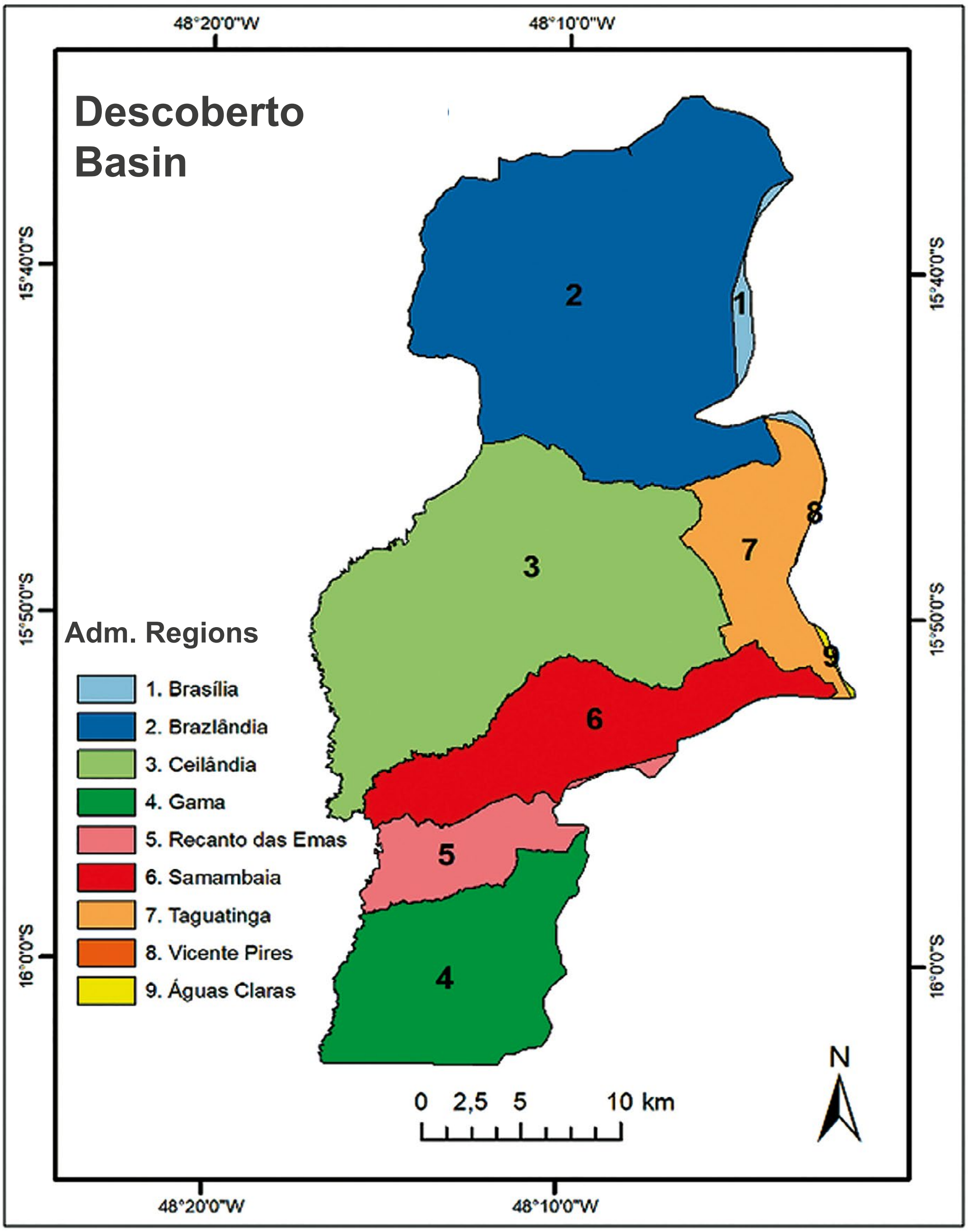
E- INDICATOR	PARAMETER			AVERAGE
	PRESSURE	STATE	RESPONSE	
Escore	1.00	1.00	0.50	**0.83**

Source: authors' elaboration

Livelihood Indicator (L)

The WSI Livelihood (L) indicator assessed the human aspects of sustainability in the Descoberto Basin (see Table 2.2), focusing on the HDI-M and its sub-indicators. HDI-M and HDI-Income were obtained separately for each one of the administrative regions of the basin (Figure 3.3), corresponding to years 2000 and 2010 *http://www.atlasbrasil.org.br/2013/pt/download/*.

FIGURE 3.3 – ADMINISTRATIVE REGIONS OF THE DESCOBERTO RIVER BASIN



Source: Geoportal/DF

The average HDI-Income in the Descoberto Basin, given its respective areas, was 0.680 in 2000, and 0.746 in 2010, with an average annual variation of 0.007. Projecting this increase linearly for 2015 and 2018, the figures of HDI-Income of 0.780 and 0.800 were found, respectively.

This represented an increase of 2.6% in the five years studied. This change, in turn, corresponded to a score of 0.75 for the Livelihood-Pressure parameter, indicating an increase in the per capita income of the Basin.

TABLE 3.12 – HDI-INCOME CHANGE IN THE DESCOBERTO BASIN

INDICATOR	VALUE	ESCORE
HDI-Income 2000	0.680	-
HDI-Income 2010	0.746	-
Annual Variation (2000-2010)	0.007	-
HDI-Income 2015	0.780	-
HDI-Income 2018	0.800	-
% Change (2015-2018)	**2.5**	**0.75**

Source: authors' elaboration

In the case of the Livelihood-State parameter, the average HDI-Income for the Descoberto River Basin, given the areas of the Basin ARs, was 0.680 in 2000, and 0.746 in 2010, with an average annual variation of 0.007 in the period. Projecting this increase linearly for 2015 and 2018, the figures of 0.780 and 0.800 for the HDI-R were found, respectively.

This represented a positive variation of 2.6% in the four years studied. This variation, in turn, corresponded to a score of 0.75 in the WSI table (Table 3.13) for the parameter, indicating an increase in the per capita income of the Basin.

TABLE 3.13 – HDI IN THE DESCOBERTO RIVER BASIN IN 2015 AND 2018 AND RESPECTIVE SCORE FOR THE LIVELIHOOD-STATE PARAMETER

INDICATOR	VALUE	ESCORE
HDI-M 2000	0.649	-
HDI-M 2010	0.761	-
Annual Variation (2000-2010)	0.011	-
HDI-M 2015	0.818	-
HDI-M 2018	0.852	**0.75**

Source: authors' elaboration

Finally, based on the HDI-M values of the Basin in 2015 and 2018, and their relative variation, the WSI Life-Response parameter was found. As the HDI-M had a variation of 2.5% in the period, the score for this parameter was 0.5 (Table 3.14).

TABLE 3.14 – HDI CHANGE IN THE DESCOBERTO BASIN IN THE PERIOD 2015-18, AND RESPECTIVE SCORE FOR THE LIVELIHOOD-RESPONSE PARAMETER

INDICATOR	VALUE	CHANGE
HDI-M 2015	0.818	-
HDI-M 2018	0.852	**2.5**
Escore	-	**0.5**

Source: authors' elaboration

The synthesis of the Livelihood indicator of the Descoberto Basin, with the respective parameter averages, is shown in Table 3.15. According to this Table, the score of the Livelihood indicator of the Descoberto Basin during the period between 2015 and 2018 was 0.67, which is considered a *medium* sustainability level.

TABLE 3.15 – SYNTHESIS OF THE LIVELIHOOD INDICATOR (L) OF THE DESCOBERTO RIVER BASIN

INDICATOR L	PARAMETER			AVERAGE
	PRESSURE	STATE	RESPONSE	
Escores	0.75	0.75	0.50	**0.67**

Source: authors' elaboration

Policy Indicator (P)

The WSI's Policy indicator used information related to legal and institutional aspects, participatory management and investment in IWRM in the Descoberto Basin.

To obtain the Policy-Pressure parameter, the HDI-Education sub-indicator was calculated for the Descoberto Basin considering the period between 2015 and 2018. After obtaining the values for 2000 and 2010 for each ARs of the Basin, the mean values of HDI-Education were weighted considering these AR areas, during those same years.

Given this annual variation in the HDI-Basin Education, the values of this indicator were linearly projected for years 2015 and 2018, which resulted in values at 0.788 and 0.842, respectively. These figures led to a variation of 6.9% in the parameter, which corresponds to a score of 0.75 (Table 3.16).

TABLE 3.16 – HDI-EDUCATION WEIGHTED TOWARDS THE DESCOBERTO BASIN AND THE POLICY-PRESSURE PARAMETER SCORE

INDICATOR	VALUE	SCORE
HDI-Education 2000 HDI- Education 2010	0.519 0.699	- -
Annual change (2000-2010)	0.018	-
HDI- Education 2015 HDI- Education 2018	0.788 0.842	- -
2015-2018 Change	**6.9%**	**0.75**

Source: authors' elaboration

In the case of the Policy-State parameter, the legal and institutional capacity of the Descoberto Basin was assessed in the period between 2015 and 2018 regarding IWRM aspects. For this purpose, a questionnaire with four questions was prepared by the Project's Technical Team and subsequently distributed by SEMA-DF to several basin managers and stakeholders.

Table 3.17 presents the results of the questionnaire responses, and Table 3.18 shows the survey results and the parameter score. According to these two Tables, the average score of the questionnaires was 10 out of 12, corresponding to a score of 0.75 in this parameter.

TABLE 3.17 – SCORE OF QUESTIONNAIRES SENT OUT TO GOVERNMENT (G) AND CIVIL SOCIETY (CS) MANAGERS. SCORE: 1 = NO; 2 = PARTIALLY; 3 = YES

MANAGER IDENTIFICATION	ARE THERE LAWS AND REGULATIONS ON INTEGRATED BASIN WATER RESOURCES MANAGEMENT (IWRM)?	ARE THESE LAWS AND REGULATIONS EFFECTIVE IN TERMS OF PROVIDING ADEQUATE IWRM POLICIES TO THE BASIN?	ARE THERE WATER RESOURCES MANAGEMENT INSTITUTIONS IN THE BASIN?	ARE THESE INSTITUTIONS EFFECTIVE IN TERMS OF ADEQUATE IWRM ACTIONS IN THE BASIN?	TOTAL
G1	2	3	3	3	11
G3	3	2	3	2	10
G4	3	3	3	3	12
G5	3	2	3	2	10
G6	3	2	3	2	10
G7	3	2	3	2	10
G8	3	2	3	2	9
SC1	2	2	3	2	10
SC2	3	2	3	2	9
SC3	2	2	3	2	10
SC4	2	2	3	2	9
SC5	3	2	2	2	9
Average	**2.7**	**2.2**	**2.9**	**2.2**	**10.0**

Source: authors' elaboration

TABLE 3.18 – CLASSIFICATION AND SCORING OF THE RESULTS OF THE QUESTIONNAIRES SENT TO MANAGERS

QUESTIONNAIRE AVERAGES	LEGAL AND INSTITUTIONAL CAPACITY	ESCORE
4	Very poor	0.00
5 a 6	Poor	0.25
7 e 8	Medium	0.5
9 e 10	**Good**	**0.75**
11 e 12	Very good	1.00

Source: authors' elaboration

As for the Policy-Response parameter, the relative change of investments in IWRM activities in the Descoberto Basin was calculated considering the period between 2015 and 2018. The results, as well as the final parameter score, are presented in Table 3.19. According to this Table, there was an increase of 0.15% in the level of IWRM investments in the Basin, which corresponds to a score of 0.5 for this parameter.

TABLE 3.19 – AMOUNTS INVESTED IN IWRM IN THE DF IN 2015 AND 2018, PERCENTAGE CHANGE IN THE PERIOD AND RESPECTIVE SCORE IN THE POLICY-RESPONSE PARAMETER

YEAR	2015	2018	% VARIATION	ESCORE
Investiment (R$)	178,043,642.28	178,315,878.93	0.15	**0.5**

Source: authors' elaboration

The summary of the Policy indicator for the Descoberto River Basin, considering the period between 2015 and 2018, is shown in Table 3.20. According to this Table, the P indicator value was 0.67, which is considered *medium*.

TABLE 3.20 – SUMMARY OF THE POLICY INDICATOR (P) FOR THE DESCOBERTO BASIN (2015-2018)

INDICATOR P	PARAMETER			AVERAGE
	PRESSURE	STATE	RESPONSE	
Escores	0.75	0.75	0.50	**0.67**

Source: authors' elaboration

Integrated Basin Sustainability

The sustainability indicators of the Descoberto Basin, during the period between 2015 and 2018, followed by the respective level and scores, are in Table 3.21.

TABLE 3.21 – SUSTAINABILITY INDEX OF THE DESCOBERTO RIVER BASIN (2015-2018)

INDICATOR	PRESSURE		STATE		RESPONSE		AVERAGE
	VALUE	ESCORE	VALUE	ESCORE	VALUE	ESCORE	
Hydrology	-	0.50	-	0.38	-	0.50	**0.46**
Environment	-0.15%	1.00	47.94%	1.00	2.3%	0.50	**0.83**
Livelihood	2.6%	0.75	0.852	0.75	4%	0.50	**0.67**
Policy	6.9%	0.75	Boa	0.75	0.15%	0.50	**0.67**
Average		**0.75**		**0.72**		**0.50**	**0.66**

Source: authors' elaboration

The global WSI score of the Descoberto Basin was 0.66, which corresponds to a *medium* sustainability level. In terms of WSI indicators (table lines), the lowest average corresponded to Hydrology (0.46), which was the limiting factor in the basin.

In the case of the averages in columns (P, S, R), the limiting factor was the Response (0.50). In terms of the individual parameters (cells in Table 3.21), the bottlenecks were the three Hydrology parameters and the four Response parameters, shown in red. These are the issues that should be prioritized in the Descoberto Basin to increase its sustainability.

Paranoá River Basin

Similar to the Descoberto River Basin, the WSI was applied to the Paranoá River Basin in the period between 2015 and 2018, and the results of its four indicators and the final index are presented in the following sub-items. As the methodology for obtaining the WSI is the same in both basins, only the main results are presented.

Hydrology Indicator (H)

Hydrology-Quantity

Considering that the Paranoá Basin has two accumulation reservoirs (Santa Maria and Paranoá), its average water supply was taken as the sum of the average annual inflows (1999-2018) and the reservoirs regulating potential, which represented 76% of their respective active volumes.

Since the active volumes of the Santa Maria and Paranoá reservoirs are 61 and 35 hm^3, respectively, a total annual volume of 73 hm^3 was added to the basin average inflow, i.e., 444.7+ 0.76*(61+35) = 517.7 hm^3/year. This was taken as the actual long-term water supply in the Paranoá Basin.

In terms of water demand in the Basin, a total of 721,608 inhabitants were supplied by the Paranoá Production System in 2018 (CAESB, 2019), using the systems implemented in Santa Maria/Torto, Gama, Cabeça de Veado, Bananal, and Lago Paranoá. The latter two having come into operation during the 2017 water crisis.

Considering the population supplied and the water supply indicated above, the basin unit water demand during the period between 1999 and 2018 was: D_a = 721,608/517.7 = 1,394 inhab/hm^3.year.

This unit water demand corresponds to a score of 0.25 in the Hydrology-Quantity-State parameter (Table 3.22). Since Da fell between 1,000 and 2,000 inhab./hm^3.year, the basin is in the imminence of water stress (FALKENMARK; WIDSTRAND 1992).

TABLE 3.22 – AVERAGE UNIT WATER DEMAND IN THE PARANOÁ RIVER BASIN, IN THE PERIOD BETWEEN 1999 AND 2018 AND RESPECTIVE PARAMETER SCORE

PERIOD	1999-2018	ESCORE
D_a (hab./hm^3.ano)	1,394	0.25

Source: authors' elaboration

In the case of the Hydrology-Quantity-Pressure parameter in the period between 2015 and 2018, the average inflow volume added to reservoir regulation amounted 408.4+73.0 = 481.8 hm^3/year, with a unit demand of D_a = 721,608/481.8 = 1,498 inhab/hm^3.year (Table 3.23). According to this Table, the increase reached ΔD_a = 7.5%, corresponding to a score of 0.50 in the Hydrology-Quantity-Pressure parameter.

TABLE 3.23 – AVERAGE UNIT WATER DEMAND IN THE PARANOÁ RIVER BASIN AND THE VARIATION BETWEEN THE PERIODS 2015-18 AND 1999-2018

PERÍODO	1999-2018	2015-2018	VARIATION	ESCORE
D_a (hab./hm^3.ano)	1,394	1,498	7.5	0.50

Source: authors' elaboration

In the case of the Hydrology-Quantity-Response parameter, a series of water management activities in the Paranoá Basin were executed, in response to the 2017 water crisis:

- Establishing two new water supply systems in the Basin, one in the Bananal river and the other in Paranoá lake, generating an additional water supply of 1.2 m3/s, equivalent to 37.8 hm3/year;
- Interconnecting the Santa Maria/Torto and Descoberto Production Systems, increasing the efficiency of water macro-allocation in the administrative regions;
- Enforcing water rationing in the ARs surrounding the basins, generating water savings of 20%;
- Conducting water saving campaigns in the media;
- Imposing contingency fee during the water crisis and using resources obtained in measures of integrated water resources management in the Basin.

Hence, the evolution in water-use efficiency in the Paranoá Basin was considered *good* in the period and corresponded to a score of 0.75 in this parameter.

The synthesis of the *Hydrology-Quantity* sub-indicator in the Paranoá River Basin is presented in Table 3.24. According to this Table, the sub-indicator level was *medium* (0.5), reflecting the basin water scarcity.

TABLE 3.24 – SYNTHESIS OF THE HYDROLOGY-QUANTITY SUB-INDICATOR IN THE PARANOÁ RIVER BASIN, DURING 2015-2018

HYDROLOGY - QUANTITY	PRESSURE	STATE	RESPONSE	AVERAGE
Figure	7.5%	1,394hab./hm^3.ano	Good	-
Escore	0.50	0.25	0.75	0.50

Source: authors' elaboration

Hydrology-Quality

In the case of the Hydrology-Quality-Pressure parameter, the average annual amount of total phosphorus in the Paranoá Basin and its main tributaries, during 2001-2018 and 2015-2018, were 0.028 and 0.020 mg/L, respectively. There was reduction in P concentrations between the two periods of 28.6%, corresponding to a score of 1.0 in this parameter (Table 3.25).

TABLE 3.25 – AVERAGE TOTAL P IN THE PARANOÁ BASIN, FOR 2015 AND 2018, RELATIVE CHANGE AND RESPECTIVE SCORE

PARAMETER	AVERAGE 2001-2018	AVERAGE 2015-2018	CHANGE%	ESCORE
Total P (mg/L)	0.028	0.020	-28.6	1.0

Source: authors' elaboration

In the case of the Hydrology-Quality-State parameter, the average WQI in the Paranoá Basin, obtained through samples from the lake and its main tributaries, during the period between 2015 and 2018, was 67.5, which corresponds to a score of 0.50 in this parameter (Table 3.26).

TABLE 3.26 – AVERAGE WQI IN THE PARANOÁ BASIN AND RESPECTIVE SCORE

PARAMETER	AVERAGE 2015-2018	ESCORE
WQI	67.5	0.50

Source: authors' elaboration

Finally, as for the Hydrology-Quality-Response parameter, a variation of 6.9% was observed between 2015 and 2018 [$\Delta WQI = (WQI_{2018}$-WQI2015)/WQI_{2018}]. This variation corresponds to a score of 0.75 in this parameter (Table 3.27).

TABLE 3.27 – WQI IN THE PARANOÁ BASIN BETWEEN 2015 AND 2018 AND RESPECTIVE SCORE

PARAMETER	AVERAGE 2015	AVERAGE 2018	VARIATION 2015-2018	ESCORE
WQI	62.7	72.5	6.9%	0.75

Source: authors' elaboration

The synthesis of the Hydrology-Quality indicator in the Paranoá River Basin is presented in Table 3.28, resulting in a average score of 0.75.

TABLE 3.28 – SYNTHESIS OF THE HYDROLOGY - QUALITY SUB-INDICATOR IN THE PARANOÁ RIVER BASIN, IN 2015-2018

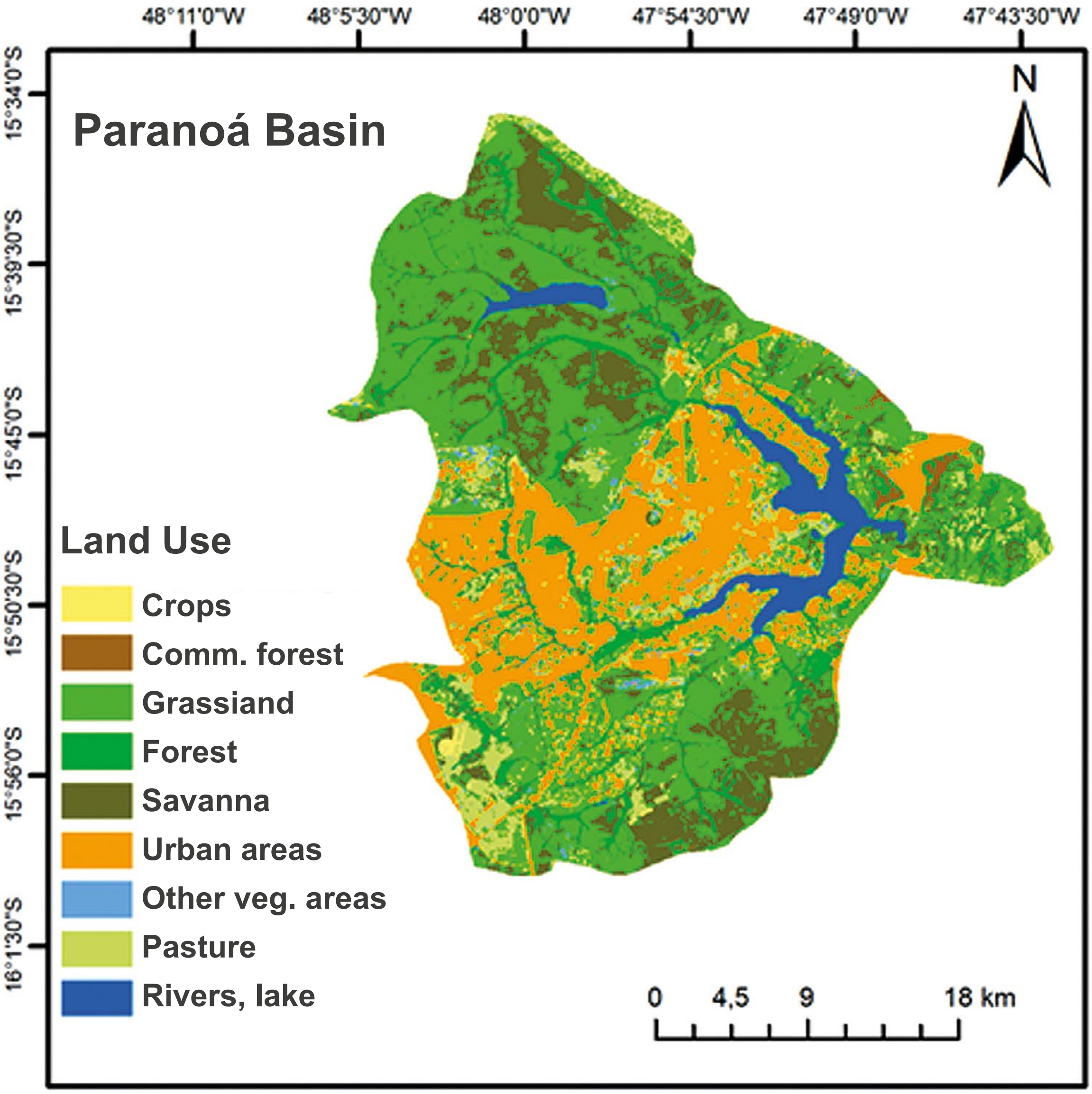
HYDROLOGY-QUALITY	PRESSURE	STATE	RESPONSE	AVERAGE
Value	-28.6%	67.5	6.9%	-
Escore	1.00	0.50	0.75	0.75

Source: authors' elaboration

Environment Indicator (E)

To obtain the Environmental Pressure Index - EPI of the Paranoá Basin, the variation of natural areas in urban and agricultural areas was calculated. Figure 3.4 presents the sum of *agricultural and pasture areas in* 2015.

FIGURE 3.4 – LAND USE IN THE PARANOÁ RIVER BASIN IN 2015



Source: authors' elaboration

Agricultural areas in the Paranoá Basin grew 1.0% between 2015-2018, from 92.63 km^2 to 93.54 km^2. Urban areas increased from 240.1 km^2 in 2015 to 245.7 km^2 in 2018, representing a growth of 2.3% (Table 3.29). Due to these changes, the EPI of the Basin reached 1.6%, corresponding to a score of 0.75 in the *Environment-Pressure* parameter.

TABLE 3.29 – WSI VALUES AND SCORES IN THE ENVIRONMENT-PRESSURE (IPE) PARAMETER IN THE PARANOÁ RIVER BASIN, BETWEEN 2015 AND 2018

AGRICULTURAL AREA IN THE BASIN (KM^2)			URBAN AREA IN THE BASIN (KM^2)			EPI	ESCORE
2015	2018	CHANGE %	2015	2018	CHANGE %		
92.63	93.54	1.0	240.11	245.71	2.3	1.65	0.75

Source: authors' elaboration

The area of native vegetation in the Paranoá Basin numbered 659.08 km^2 in 2018, representing 62.4% of the total basin area. This corresponded to a score of 1.00 in the *Environment-State* parameter, indicating a high level of environmental conservation in the Basin.

As for the *Environment-Response* parameter, the change in conserved/managed areas in the Paranoá River Basin was calculated considering the period between 2015 and 2018. In 2018, there were 66 parks and other Conservation Units in the Basin. However, there has not been any new park or Conservation Unit between 2015 and 2018.

In the analysis, the Areas of Relevant Ecological Interest (ARIEs) and Environmental Protection Areas (APAs) in the Basin were not included, since the former are not restrictive enough and the latter overlap with other UCs in the Basin area. Thus, it was found that, between 2015 and 2018, forest formations inside parks and other UCs in the Paranoá Basin increased from 41.7 to 49.4 km^2, a 18% increase.

In the case of savanna formations, these increased from 147.19 km^2 to 165.18 km^2 in the same period, a 12% increase. Rural formations, in turn, suffered a 14% reduction during in the period (Table 3.30). The 1.0% reduction in effective natural areas in the Basin UCs during the period corresponded to a score of 0.25 in the WSI's *Environment-Response* parameter.

TABLE 3.30 – TYPES OF LAND-USE IN PARKS AND CONSERVATION UNITS IN THE PARANOÁ BASIN (EXCEPT APAS AND ARIES)

TITLES	AREA 2015 (KM²)	AREA 2018 (KM²)	VARIATION
Forest	41.71	49.36	18
Savanna	147.19	165.18	12
Grassland	204.84	176.90	-14
Total	393.74	391.44	-1.0
Escore	-	-	0.25

Source: authors' elaboration

The summary of the Paranoá Basin's Environment indicator is presented in Table 3.31. According to this Table, the Environment indicator scored 0.67, which is considered *medium* (CHAVES E ALÍPAZ 2007).

TABLE 3.31 – SYNTHESIS OF THE ENVIRONMENT INDICATOR IN THE PARANOÁ RIVER BASIN, IN THE PERIOD 2015-18

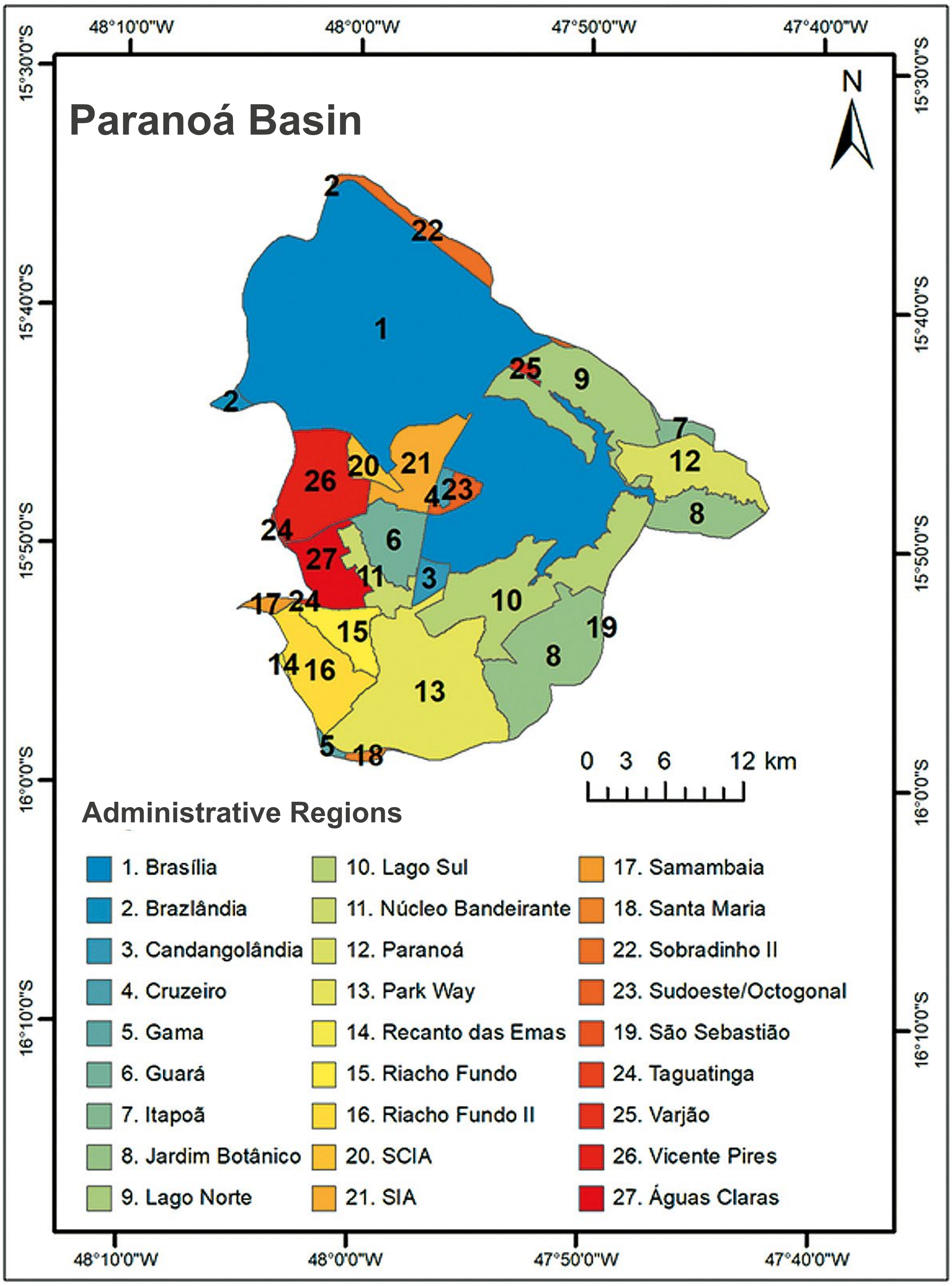
ENVIRONMENT (E)	PRESSURE	STATE	RESPONSE	AVERAGE
Value	1.6%	62.4%	-1.0%	-
Escore	0.75	1.00	0.25	0.67

Source: authors' elaboration

Livelihood Indicator (L)

In this indicator, the human aspects of sustainability in the Paranoá River Basin were evaluated, focusing on the HDI-M and respective sub-indicators. The HDI-M and HDI-Inc values were obtained from http://www.atlasbrasil.org.br/2013/pt/download/, for each of the ARs that are part of the Paranoá Basin (Figure 3.5).

FIGURE 3.5 – ADMINISTRATIVE REGIONS (ARS) IN THE PARANOÁ RIVER BASIN IN 2018



Source: Geoportal/DF

RESULTS

In the case of the *Livelihood-Pressure* parameter, the weighted average value (by area) of the HDI-Inc for the Paranoá River Basin was 0.891 in 2000, and 0.939 in 2010, with an average annual increase of 0.005 during this period. Considering that HDI data and sub-indicators regarding the Federal District's ARs were available only for years 2000 and 2010, this annual rate was linearly grossed up for 2015 and 2018.

Thus, the projected HDI-Income for the Paranoá River Basin in 2015 amounted 0.962, and 0.977 in 2018, representing a positive variation of 1.5% in the four years analyzed (Table 3.32) and indicating an increase in the per capita income. This variation, in turn, corresponded to a score of 0.75 in the *Livelihood-Pressure* parameter.

TABLE 3.32 – HDI-INC IN 2015 AND 2018, AND ITS VARIATION IN THE PARANOÁ BASIN

INDICATOR	VALUE	ESCORE
IDH-Income 2000 IDH-Income 2010	0.891 0.939	- -
Annual variation (2000-2010)	0.005	-
IDH-Income 2015 IDH-Income 2018	0.962 0.977	- -
Change % (2015-2018)	**1.5**	**0.75**

Source: authors' elaboration

In the case of the *Livelihood-State* parameter, after the 2000's and 2010's HDI-M values were linearly grossed up in order to estimate 2015 and 2018, these years were at 0.935 and 0.959, respectively (Table 3.33). The 0.959 weighted average value for the basin HDI-M in 2018, in turn, corresponds to a score of 1.00 in the *Livelihood-State* parameter, indicating a high level of human development.

TABLE 3.33 – HDI-M IN THE PARANOÁ RIVER BASIN, IN 2015-2018, AND THE SCORE OF THE LIVELIHOOD-STATE PARAMETER

INDICATOR/YR	VALUE
IDH-M 2000 IDH-M 2010	0.813 0.894
Annual variation (2000-2010)	0.008
IDH-M 2015 IDH-M 2018	0.935 0.959
Escore	**1.00**

Source: authors' elaboration

As shown in Table 3.34, the variation in the Basin's weighted HDI-M between 2015 and 2018 stood at 2.5%, corresponding to a score of 0.5 in the WSI's *Livelihood-Response* parameter.

TABLE 3.34 – HDI VARIATION IN THE PARANOÁ RIVER BASIN IN 2015-2018 AND SCORE

INDICATOR/YR	VALUE
IDH-M 2015 IDH-M 2018	0.935 0.959
Variation 2015-2018	2.5
Escore	**0.50**

Source: authors' elaboration

The summary of the *Livelihood* (L) indicator in the Paranoá River Basin is presented in Table 3.35. The indicator score was 0.75, reflecting the high HDI values.

TABLE 3.35 – SYNTHESIS OF THE LIVELIHOOD INDICATOR IN THE PARANOÁ RIVER BASIN, IN 2015-2018

LIVELIHOOD (L)	PRESSURE	STATE	RESPONSE	AVERAGE
Value	1.5%	0.959	2.5%	-
Escore	0.75	1.00	0.50	0.75

Source: authors' elaboration

Policy Indicator (P)

As in the case of the Descoberto Basin, the variation of the weighted average HDI-Education in the Paranoá Basin was calculated considering the period between 2000 and 2010, and the annual variation was grossed up for 2015 and 2018. The results are in Table 3.36.

TABLE 3.36 – IDH-EDUCATION NA BACIA DO RIO PARANOÁ E SUA CHANGE NO PERÍODO 2015-2018

INDICATOR/YR	VALUE
IDH-Education 2000 IDH- Education 2010	0.717 0.832
Annual variation (2000-2010)	0.011
IDH- Education 2015 IDH- Education 2018	0.889 0.924
Variation between 2015 e 2018	4.0%
Escore	**0.75**

Source: authors' elaboration

According to table 3.36, the variation in the Basin's HDI-Education stood at 4%, corresponding to a score of 0.75 in the *Policy-Pressure* parameter.

As for the *Policy-State* parameter, the questionnaires distributed to thirteen water and environmental managers in the Federal District, regarding the level of Integrated Water Resources Management in the Basin, revealed an average value of 10 (out of 12), corresponding to one score of 0.75 in this parameter.

Similarly to the Descoberto Basin, the WSI Policy-Response parameter in the Paranoá Basin was considered, using the growth in expenditure and investment related to Integrated Water Resources Management between 2015 and 2018.

To this end, it was assumed that the growth in the IWRM expenditures was the same as that which occurred in the entire Federal District region, as previously indicated. Thus, Table 3.37 shows the variation in IWRM investments between 2015 and 2018.

TABLE 3.37 – IWRM INVESTMENTS IN THE DF IN 2015 AND 2018 AND PERCENTAGE VARIATION BETWEEN THESE YEARS, THE LATTER ALSO USED FOR THE PARANOÁ RIVER BASIN. ADAPTED FROM CHAVES & ALÍPAZ (2007)

YEAR	2015	2018	VARIATION	ESCORE
Investimento (R$)	178,043,642.28	178,315,878.93	0.15%	**0.50**

Source: authors' elaboration

According to the Table above, the positive variation of 0.15% in investment between 2015 and 2018 in the Paranoá Basin corresponded to a score of 0.50 in the Policy-Response parameter. The summary of the Policy indicator for the Paranoá River Basin between 2015 and 2018 is shown in Table 3.38. According to this Table, the indicator value was 0.67.

TABLE 3.38 – SYNTHESIS OF THE POLICY INDICATOR (P) IN THE PARANOÁ RIVER BASIN (2015-2018)

INDICATOR P	PARAMETER			AVERAGE
	PRESSURE	STATE	RESPONSE	
Escores	0.75	0.75	0.50	**0.67**

Source: authors' elaboration

Integrated Basin Sustainability

Table 3.39 presents the WSI matrix for the Paranoá Basin between 2015 and 2018. According to this Table, the global WSI average was 0.68, which classifies as *medium sustainability*.

TABLE 3.39 – SUSTAINABILITY INDEX IN THE PARANOÁ RIVER BASIN, BETWEEN 2015 AND 2018

INDICATOR	PRESSURE		STATE		RESPONSE		AVERAGE
	VALUE	*ESCORE*	*VALUE*	*ESCORE*	*VALUE*	*ESCORE*	
Hydrology	-	0.75	-	0.38	-	0.75	**0.63**
Environment	1.6%	0.75	62.4%	1.00	-1%	0.25	**0.67**
Livelihood	1.5%	0.75	0.959	1.00	2.5%	0.50	**0.75**
Policy	4.0%	0.75	Bom	0.75	0.15%	0.50	**0.67**
Average		**0.75**		**0.78**		**0.50**	**0.68**

Source: authors' elaboration

The limiting sustainability indicator in Table 3.39 was *Hydrology* (0.63) and Response was the column with the lowest overall average (0.50). The red cells in Table 3.39 indicate the parameters that have limited the sustainability in the Basin and which require prioritization.

The slightly higher WSI score in the Paranoá Basin, in relation to the Descoberto Basin (0.68 against 0.66, respectively), is a result of a lower level of water stress in the former, as indicated by the average Hydrology score (0.63 against 0. 46, respectively).

Comparison with other Latin American Basins

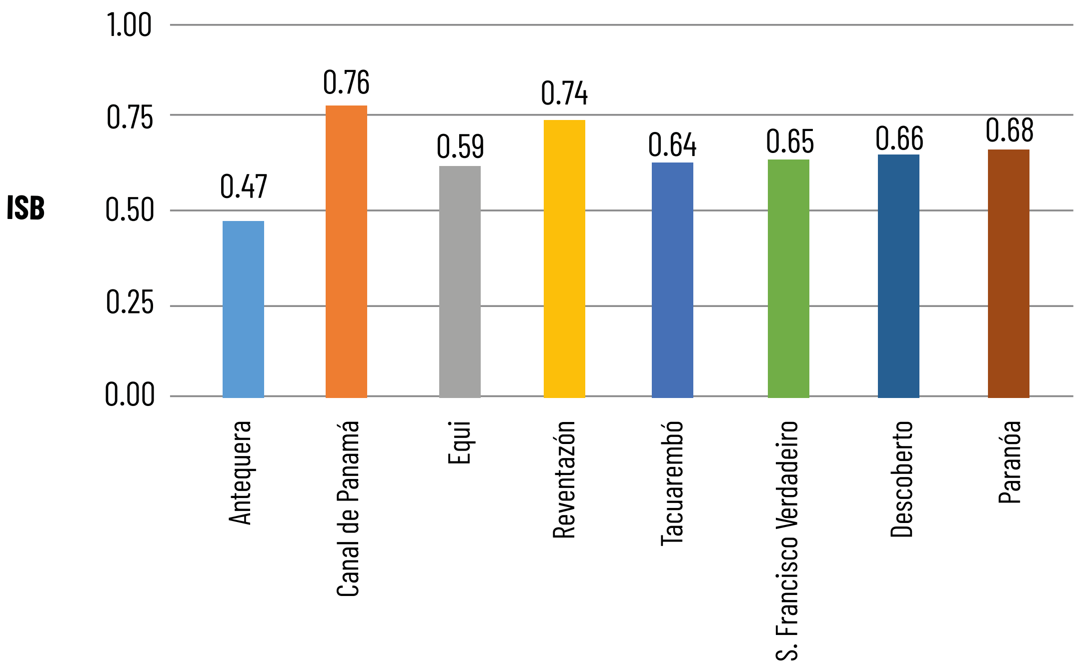
The WSI in the Descoberto and Paranoá Basins, presented above, were compared with those from other Brazilian and Latin American basins, in order to assess their degree of integrated sustainability in national and international terms. The description of the other basins analyzed are shown in Table 3.40, and the results of the WSI index for each one of them are in Figure 3.6.

TABLE 3.40 – DESCRIPTION OF BRAZILIAN AND LATIN AMERICAN BASINS, ACCORDING TO THE PRESENT STUDY

BASIN	COUNTRY	AREA (KM^2)	PERIOD
Antequera	Bolivia	226	1997-2001
Canal de Panamá	Panama	3,000	2003-2007
Elqui	Chile	9,826	2001-2005
Reventazón	Costa Rica	3,000	2001-2005
Tacuarembó	Uruguay	16,900	1999-2004
S. Francisco Verdadeiro	Brazil	2,200	1996-2000
Descoberto	Brazil	801.2	2015-2018
Paranoá	Brazil	1,056	2015-2018

Source: authors' elaboration

FIGURE 3.6 – SUSTAINABILITY COMPARISON AMONG THE DESCOBERTO AND PARANOÁ BASINS AND OTHER BRAZILIAN AND FOREIGN BASINS



Source: Chaves (2011)

As shown in Figure 3.6, the Descoberto and Paranoá Basins presented WSI values slightly above the WSI average (0.64) of the six Brazilian and Latin American basins. With the exception of the Bolivian basin (low sustainability), all others had average levels of integrated sustainability, with the WSI varying between 0.5 and 0.8.

Although the WSI values of the basins in Figure 3.6 are similar, the bottlenecks (parameters with scores ≤ 0.5) were different in each of them (CHAVES, 2011), which means different actions and initiatives are required to increase their integrated sustainability.

WATER SUSTAINABILITY

The results of the inter-annual water sustainability analysis in the Descoberto and Paranoá Basins, considering the present scenario, are shown below. Additionally, the results of water sustainability in the Ribeirão Rodeador Basin considering current and future scenarios of water supply and demand are presented and discussed.

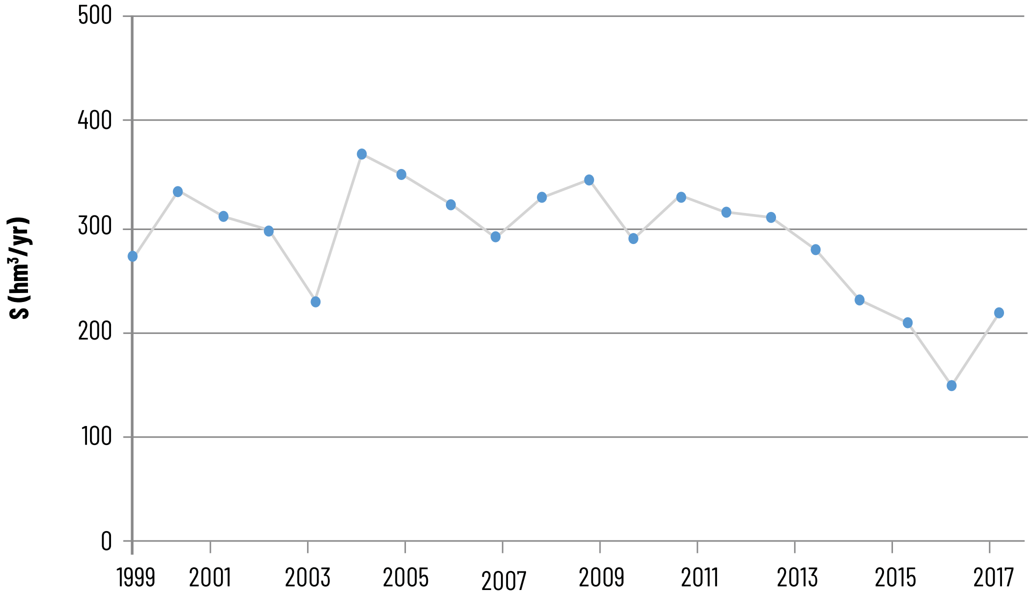
Descoberto River Basin

In order to estimate water sustainability in the Descoberto River Basin, the water supply and demand in the Basin, in the present scenario, was assessed. The results are as follows.

Water Supply

The effective annual water supply in the Descoberto Basin was assumed as the reservoir average inflows (1999-2018) added to the reservoir regulation capacity (76% of its active volume). This is shown in Figure 3.7.

FIGURE 3.7 – WATER SUPPLY IN THE DESCOBERTO BASIN BETWEEN 1999 AND 2018



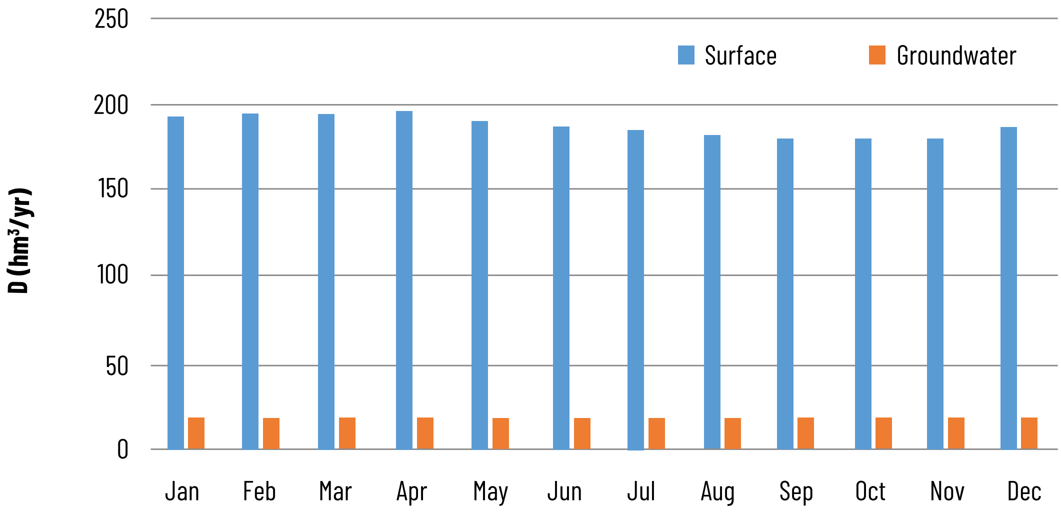
Source: authors' elaboration

Considering that the average annual inflow in the period was 233.7 hm^3/year, and that the active volume of the Descoberto reservoir is 72.2 hm^3, the effective basin water supply was S = 233.7 + 0.76*72.2 = 288.6 hm^3/year.

Water Demand

Figure 3.8 shows the monthly surface and underground licensed volumes of the Descoberto Basin in 2017, which were used to assess the basin's average annual water demand. As indicated earlier, the water demand in the basin was the sum of the annual surface licensed volume and 50% of the average annual groundwater licensed volume, as displayed in Table 3.41. According to that Table, the water demand in the Descoberto Basin, considering surface and underground uses, was 197.6 hm^3/year.

FIGURE 3.8 – SURFACE AND UNDERGROUND LICENSED WATER VOLUMES IN THE DESCOBERTO BASIN



Source: Unesco (2017)

TABLE 3.41 – AVERAGE ANNUAL SURFACE AND GROUNDWATER LICENSED VOLUMES AND EFFECTIVE ANNUAL WATER DEMAND IN THE DESCOBERTO BASIN

VARIABLE	D_{SF}	D_{GW}	DEMAND
	---------- HM³/YR ----------		
Value	188.7	17.8	197.6

Source: authors' elaboration

Water Sustainability of the Basin in the Current Scenario

The water sustainability of the Descoberto Basin in the current scenario was calculated using the WRSD index (equation 2.1). Considering that the water supply in the Basin was 288.6 hm^3/year, and that the water demand was 197.6 hm^3/year, the inter-annual water sustainability of the Basin was WRSD = (288.6-197.6) / 288.6 = 0.32.

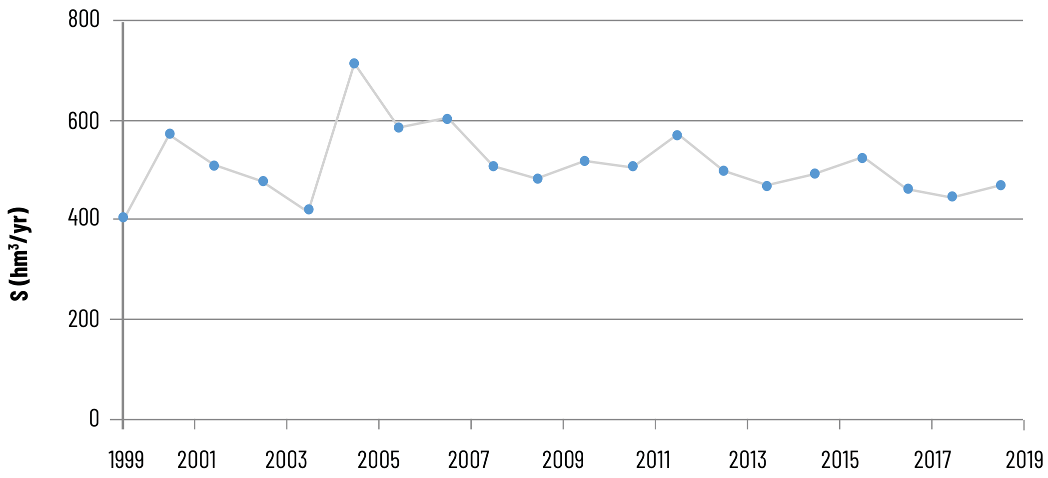
According to Xu et al. (2002), this value corresponds to a medium water sustainability. However, it is much closer to a water stress condition (0.2) than to the what is considered to be a comfort level (0.8).

Paranoá River Basin

Water Supply

The water supply in the Paranoá Basin was obtained by summing the average annual inflow and 76% of the active storage volume of the Paranoá and Santa Maria reservoirs (average annual flow regulating capacity). Figure 3.9 shows the water supply in the Basin, in the period between 1999 and 2018. The water supply in the Paranoá Basin was 517.7 hm^3/year.

FIGURE 3.9 – WATER SUPPLY IN THE PARANOÁ RIVER BASIN BETWEEN 1999 AND 2018

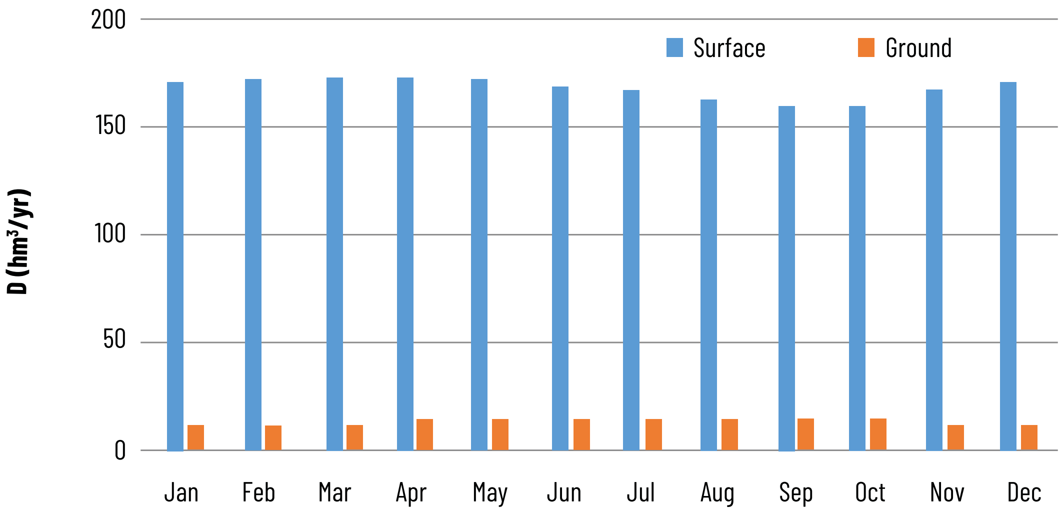


Source: authors' elaboration

Water Demand

Figure 3.10 shows the monthly surface and groundwater licensed volumes in the Paranoá Basin, which was used to assess the water demand.

FIGURE 3.10 – SURFACE AND UNDERGROUND LICENSED VOLUMES IN THE PARANOÁ RIVER BASIN



Source: Adasa (2017)

As indicated above, the water demand in the basin was the sum of the average annual licensed surface volume and half of the underground volume, as shown in Table 3.42. According to that Table, the water demand in the Paranoá Basin, considering surface and groundwater uses, was 175.6 hm^3/year.

TABLE 3.42 – AVERAGE SURFACE AND UNDERGROUND LICENSED VOLUMES AND WATER DEMAND IN THE PARANOÁ BASIN

VARIÁVEL	D_{SUR}	D_{GW}	DEMAND
	---------- HM^3/YR ----------		
Value	168.8	13.7	175.6

Source: authors' elaboration

Basin Water Sustainability

Considering that the water supply in the Paranoá Basin was 517.7 hm^3/year, and that the effective demand was 175.6 hm^3/year, the inter-annual water sustainability in the current scenario was WRSD = (517.7-175.6) / 517.7 = 0.66. According to Xu et al. (2002), this corresponds to a *medium* water sustainability level.

Ribeirão Rodeador Basin

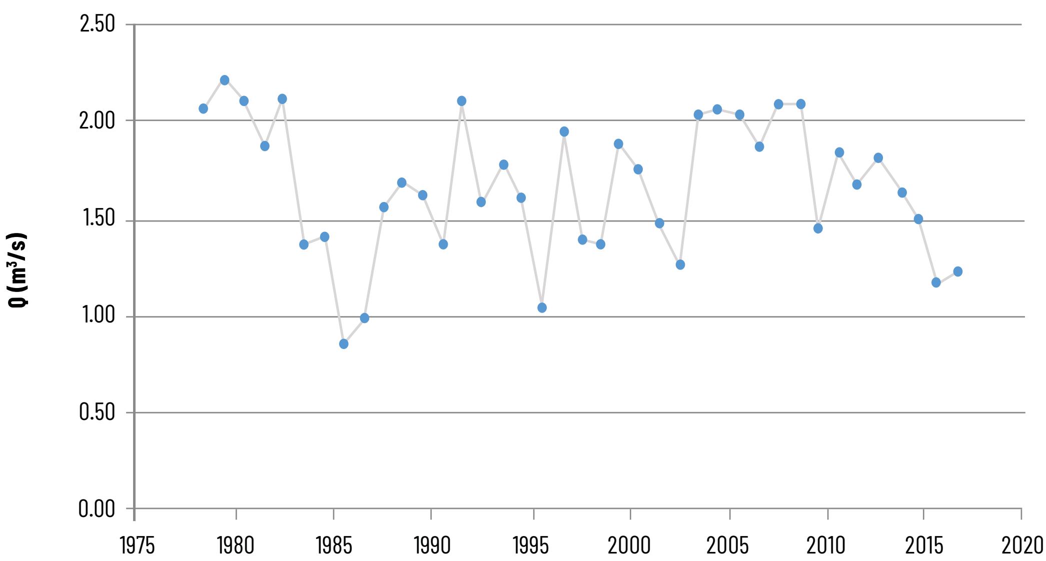
Water Supply in the Present Scenario

Since the Rodeador is an unregulated basin, the water supply, in the present scenario, was calculated based on its long-term average flow, which was obtained from gaging station No. 60435200, and corresponds to the period between 1979 and 2017 (N = 39 years).

The streamflow time series analyzed was went through a reconstitution of its natural flow (OLIVEIRA et al., 2008) to remove the irrigation use deviations (0.38 m^3/s), resulting in the natural water supply condition of the basin (ONS, 2003).

Similarly to the Descoberto Basin, the environmental flow in the Rodeador Basin (0.14 m3/s), estimated using flow regionalization (CHAVES et al., 2002), was deducted from the average naturalized flow, to obtain the basin water supply (Table 3.43). The Descoberto environmental flow was used as a base (0.6 m^3/s).

FIGURE 3.11 – ANNUAL WATER SUPPLY IN THE RIBEIRÃO RODEADOR (1979-2017), AFTER THE NATURAL FLOW RECONSTITUTION AND THE ENVIRONMENTAL FLOW DEDUCTION



Source: authors' elaboration

TABLE 3.43 – AVERAGE STREAMFLOW, WATER SUPPLY IN THE RODEADOR BASIN AND RESPECTIVE STANDARD DEVIATIONS

VARIÁVEL	Q_M	SD	Q	SD
	M^3/S	M^3/S	HM^3/YR	HM^3/YR
Value	1.66	0.36	52.3	11.3

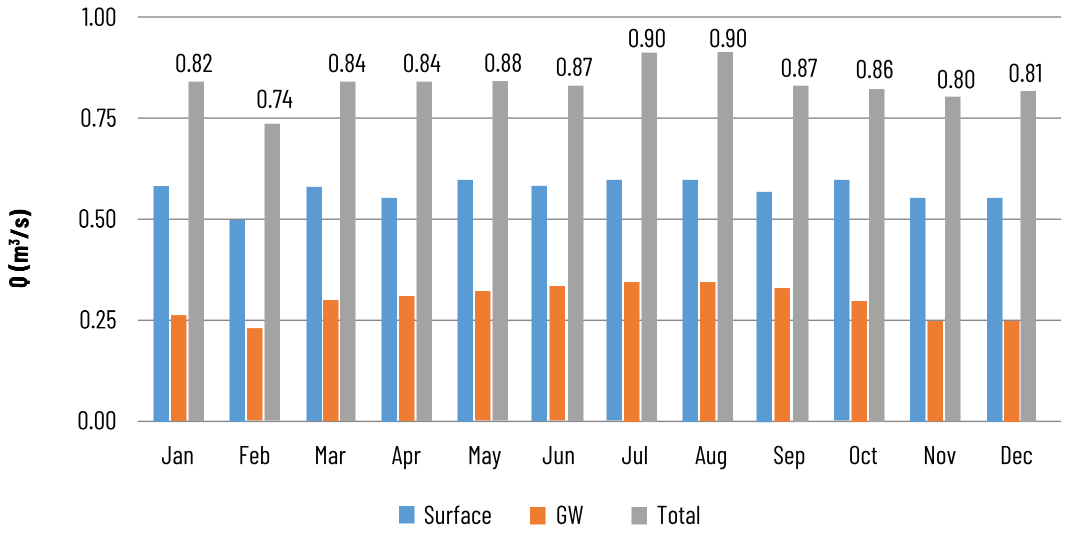
Source: authors' elaboration

As shown in Table 3.43, the water supply in the Rodeador Basin was 1.66 m^3/s, which is equivalent to a average water supply of 52.3 $hm^3/year$. This value was used to assess the water sustainability of the Basin in the present scenario.

Basin Water Demand in the Present Scenario

The water demand in the Rodeador Basin was calculated using the surface and groundwater licensed volumes in the Basin (Figure 3.12). Both water sources are used to irrigate 2,921 ha of horticulture and 238 ha of orchards. A small volume is used for human supply (0.04 m^3/s) (UNESCO, 2017), which is included in the licensed volumes.

FIGURE 3.12 – SURFACE AND UNDERGROUND LICENSED WATER VOLUMES IN THE RODEADOR BASIN IN THE PRESENT SCENARIO



Source: Unesco (2017)

Due to the local hydrogeology and the partial capture of the Ribeirão Rodeador base flow by the existing tubular wells, it was assumed that the total effective annual demand for water in the Basin was the sum of the surface licensed volume and half the groundwater licensed volume (Table 3.44).

TABLE 3.44 – AVERAGE SURFACE AND GROUNDWATER LICENSED VOLUMES AND WATER DEMAND IN THE RODEADOR BASIN

VARIABLE	D_{SUR}	D_{GW}	DEMAND
	———————— HM³/YR ————————		
Value	17.6	9.0	22.1

Source: authors' elaboration

According to Table 3.44, the water demand in the Rodeador Basin was 22.12 hm^3/year, which is equivalent to 0.70 m3/s. This was the value used to assess water sustainability, based on the WRSD index.

Water Sustainability in the Current Scenario

Considering that the water supply in the Rodeador Basin was 52.3 hm^3/year, and that the effective demand was 22.1 hm^3/year, the inter-annual water sustainability of the Basin, in the current scenario, was (52, 3 - 22.1) / 52.3 = 0.58. This value, according to Xu et al. (2002), is considered a *medium* level of water sustainability.

Water Sustainability in Future Scenarios

The water supply in the Rodeador Basin was calculated for future climate scenarios (RCP 4.5 and 8.5, in 2040 and 2070). The future basin water *demand*, on the other hand, used water demand projections for 2026 (UNESCO, 2017), i.e., 0.72 m^3/s. Table 3.45 presents the results of water supply and demand in the Rodeador Basin, as well as the WRSD index, in future scenarios.

TABLE 3.45 - ANNUAL AVERAGE P AND T FOR FUTURE CLIMATE SCENARIOS IN THE RODEADOR BASIN, AS WELL AS WATER SUPPLY (S), DEMAND (D) AND THE WRSD INDEX

YEAR	SCENARIO	T (ºC)	P (MM)	O (M^3/S)	D (M^3/S)	WRSD	LEVEL
2040	**RCP 4.5**	23.4	1463.5	1.29	0.72	0.44	Medium
2040	**RCP 8.5**	24.8	831.8	0.21	0.72	0.00	Low
2070	**RCP 4.5**	24.9	939.2	0.31	0.72	0.00	Low
2070	**RCP 8.5**	26.8	678.5	0.06	0.72	0.00	Low

Source: authors' elaboration

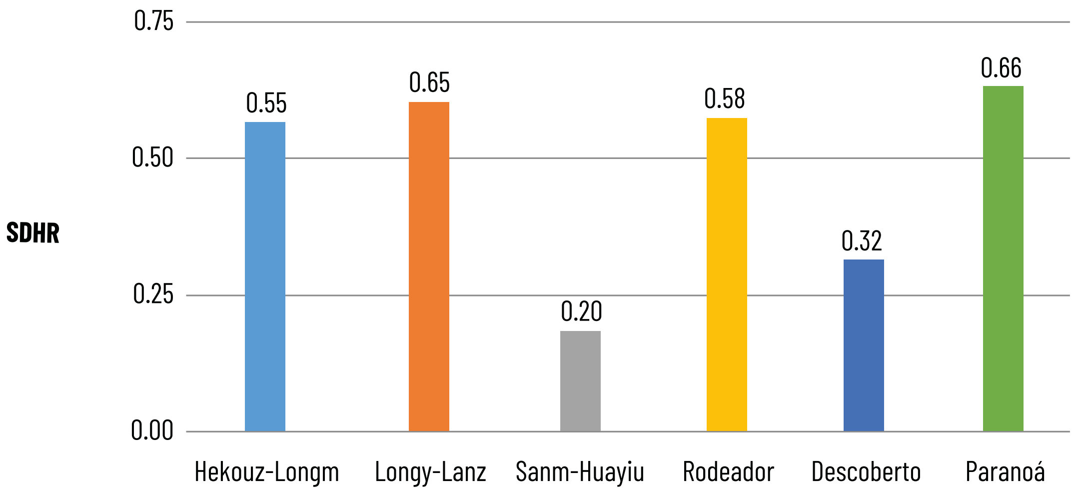
According to Table 3.45, the water sustainability in the Rodeador Basin, which in the present scenario was estimated at 0.58 (medium), would be drastically reduced in future water demand climate scenarios, varying between 0.44 (RCP 4.5-2040) and zero, in the other three scenarios.

This drastic reduction in water sustainability would happen mainly due to a strong reduction in annual precipitation in the Basin in future scenarios, significantly reducing the water supply. The increase in temperature and in water demand also contributed to a lesser degree to the WRSD reduction.

WRSD Comparison with other Basins

Figure 3.13 shows the present water sustainability values in the Descoberto Basin – which were estimated based on the WRSD (Xu et al.; 2002) – in comparison with other Brazilian and foreign basins.

FIGURE 3.13 –WATER SUSTAINABILITY IN THE DESCOBERTO, PARANOÁ AND RODEADOR BASINS AND THREE CHINESE BASINS



Source: *Xu et al.* (2002)

According to Figure 3.13, the Rodeador, Paranoá and Descoberto Basins are in the medium range of WRSD (0.2-0.8), although the latter is near the lowest limit of water sustainability (0.2).

WATER RISK IN THE RODEADOR BASIN

The intra-annual water risk in the Rodeador Basin, in the current and future scenarios of climate and water demand, was calculated using the Water Risk Index, which was developed in the present study. The results are presented below, for the Rodeador Basin.

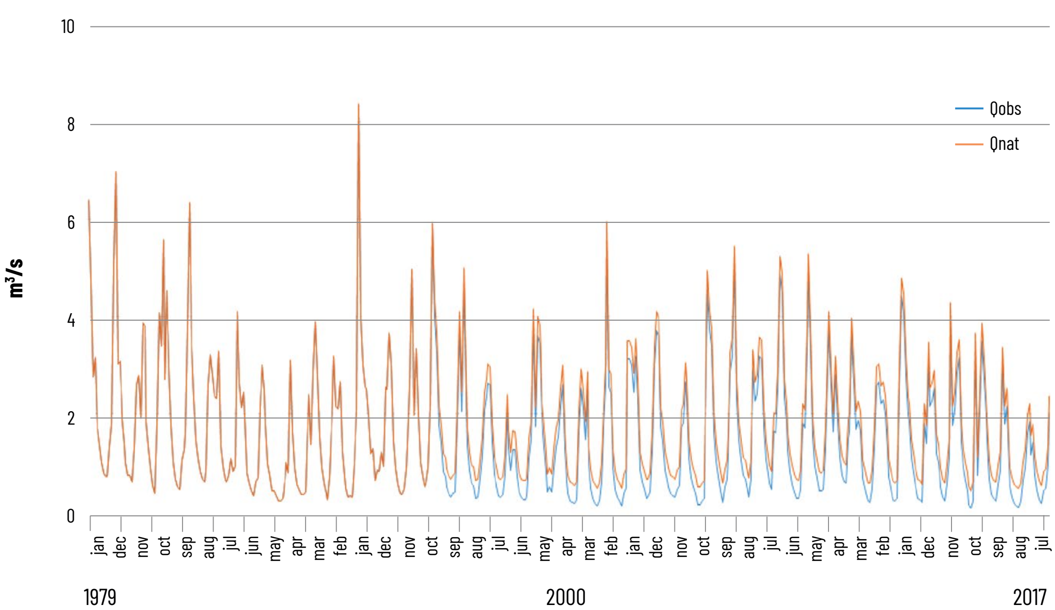
Water Risk in the Current Scenario

The intra-annual water risk in the Rodeador Basin in the current scenario was calculated according to data on present basin water supply (1979-2017) and demand (2017), and the results are presented below.

Water Supply in the Present Scenario

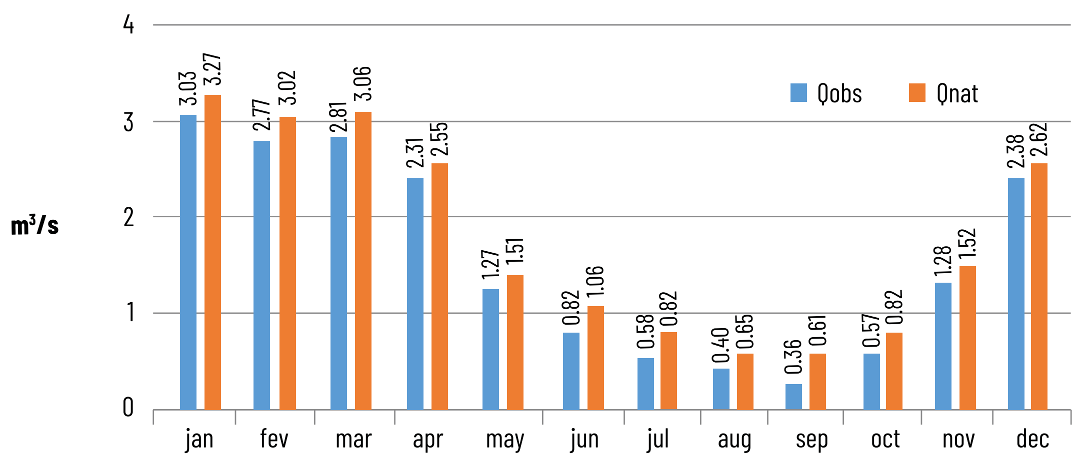
The time series of monthly natural flows Rodeador river, in the period between 1979 and 2017, after reconstitution, is displayed in Figure 3.14. Figure 3.15 shows the monthly averages of the Rodeador river's natural flows.

FIGURE 3.14 – MONTHLY OBSERVED AND NATURAL FLOW PATTERNS IN THE RODEADOR RIVER (1979-2017)



Source: authors' elaboration

FIGURE 3.15 –AVERAGE MONTHLY OBSERVED AND NATURAL FLOWS PATTERNS IN THE RODEADOR RIVER (1979-2017)



Source: authors' elaboration

RESULTS

The average monthly Q_{nat}, in orange in Figure 3.15, were used as the average monthly water supply, as they represent the average intra-annual variability of the basin's natural flows. The long-term average annual flow of the series displayed in Figure 3.15 was 1.79 m³/s. This and the other statistics of the monthly natural flow series are presented in Table 3.46.

TABLE 3.46 – STATISTICS OF MONTHLY NATURAL FLOWS IN THE RODEADOR RIVER (1979-2017)

VARIABLE	Q_{MEA}	Q_{MAX}	Q_{MIN}	S.D.
	M³/S			
Value	1.79	3.27	0.61	1.04

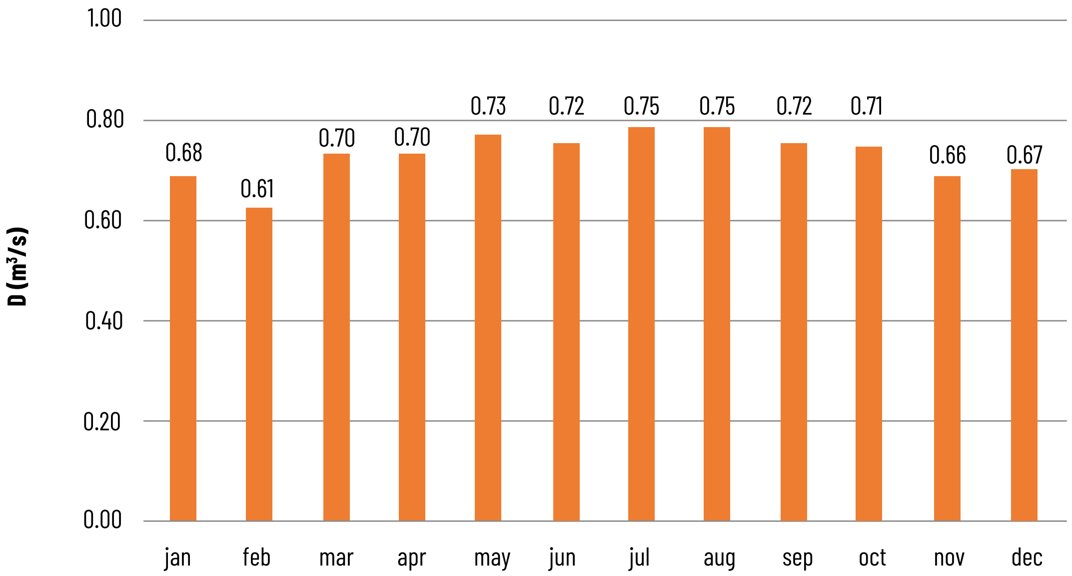
Source: authors' elaboration

Considering the Rodeador Basin's small size, its long profile and the high porosity and conductivity of its aquifer (ADASA, 2018), it was assumed that, in the long term and under natural conditions (without pumping wells), the drainage network received all the discharge from its aquifers through baseflow (ALBUQUERQUE; CHAVES, 2011). Thus, the surface water supply in the basin, estimated above, indirectly includes the groundwater supply.

Water Demand in the Present Scenario

The intra-annual water demand in the present scenario was calculated using the current average annual demand, indicated above (0.70 m³/s), and the monthly demand was considered the monthly licensed volumes (Figure 3.12). Thus, Figure 3.16 presents the average monthly demand in the Rodeador Basin in the present scenario.

FIGURE 3.16 – AVERAGE MONTHLY DEMAND IN THE RODEADOR BASIN IN THE PRESENT SCENARIO



Source: authors' elaboration

RESULTS

Water Risk in the Rodeador Basin in the Present Scenario

In order to correctly apply equation 2.8 and calculate the water risk in the Rodeador, the normality of the distributions of water supply and demand was verified. As the K-S statistics were below the Kolmogorov-Smirnov 95% probability level (0.38), the water supply and demand distributions were considered as normally distributed.

Thus, the intra-annual water risk in the Rodeador Basin, estimated by the probability of failure (pf) in the current scenario, and using the basin water supply and demand distributions, is presented in Table 3.47.

TABLE 3.47 – INTRA-ANNUAL WATER RISK (IWR) IN THE RODEADOR BASIN IN THE PRESENT SCENARIO

INTRA-ANNUAL WATER RISK		
MONTH	SUPPLY M³/S	DEMAND M³/S
Jan.	3.27	0.68
Feb.	3.02	0.61
Mar.	3.06	0.70
Apr.	2.55	0.70
May.	1.51	0.73
Jun.	1.06	0.72
Jul.	0.82	0.75
Aug.	0.65	0.75
Sep.	0.61	0.72
Oct.	0.82	0.71
Nov.	1.52	0.66
Dec.	2.62	0.67
Average	1.79	0.70
D.P.	1.04	0.04
$r_{O,D}$	-0.69	
IWR (p_f)	**15.3%**	

Source: authors' elaboration

According to Table 3.47, the *intra-annual* water risk in the Rodeador Basin, in the present scenario, was 15.3%. In practical terms, this means that water demand would exceed the water supply 1.5 times every 10 years. This is due to the fact that, during the drought season in certain years, water supply would be below demand, causing a collapse, even when the average annual supply exceeds the demand.

As indicated in Table 3.47, the basin water supply is negatively correlated to the demand (r = -0.69), which contributed to the pf surpassing the acceptable limit of 5% (CHAVES; LORENA; 2019).

Water Risk in Future Scenarios

In order to estimate the intra-annual water risk of the Ribeirão basin, different future scenarios of water supply and demand were used. The results are below.

Water Supply in Future Scenarios

The intra-annual water supply in the Rodeador Basin in 2040 and 2070 was calculated using the IPCC RCP 4.5 and 8.5 emission scenarios, with average annual P and T values, from the HadGEM2/Eta model (5 x 5 km) projections.

After the average annual P and T values were calculated from the Basin through spatial analysis in the GIS, the average annual evapotranspiration was calculated through the Holland model (equation 2.11) and the average annual flow through the Gardner model (equation 2.10), for years 2040 and 2070, considering the two GHG emission scenarios mentioned above.

The average monthly flows in the different climate scenarios were obtained considering a linear relationship between the monthly averages and the annual averages of the historical flow series in the Basin (Table 3.48).

TABLE 3.48 – MONTHLY WATER SUPPLY IN THE RODEADOR BASIN, BASED ON HADGEM2/5 KM MODEL PROJECTIONS AND HOLLAND (1978) AND GARDNER (2009) MODELS

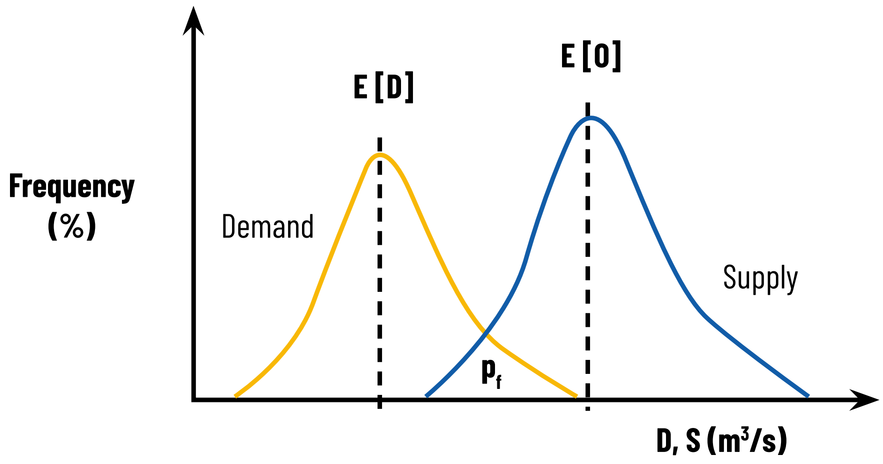
MONTH	MONTHLY WATER SUPPLY / MODEL HADGEM2/5KM				
	1979-2017	2040		2070	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	---------------(M³/S)---------------				
Jan.	3.27	2.35	0.38	0.57	0.12
Feb.	3.02	2.17	0.35	0.53	0.11
Mar.	3.06	2.20	0.35	0.54	0.11
Apr.	2.55	1.83	0.30	0.45	0.09
May.	1.51	1.09	0.18	0.27	0.05
Jun.	1.06	0.77	0.12	0.19	0.04
Jul.	0.82	0.59	0.10	0.14	0.03
Aug.	0.65	0.47	0.08	0.11	0.02
Sep.	0.61	0.44	0.07	0.11	0.02
Oct.	0.82	0.59	0.09	0.14	0.03
Nov.	1.52	1.09	0.18	0.27	0.06
Dec.	2.62	1.89	0.30	0.46	0.10

Source: authors' elaboration

As shown in Table 3.48, there would be a drastic reduction in water supply in the Rodeador Basin in all future scenarios, compared to the present conditions. These reductions result from a significant increase in the average annual temperature, increasing evapotranspiration in the basin and, more importantly, they are a consequence of the strong reduction in annual precipitation.

Although this hydrological analysis does not include the basin's minimum flows, used for water licensing purposes, the water risk uses the distribution of average monthly flows, incorporating both the inter-annual variability of the historical series, as well as the intra-annual variability (dry and rainy periods). Since the lower tail of the water supply distribution (Figure 3.17) includes the minimum flows of the series, the reference flows are indirectly included in the stochastic analysis of the WRI.

FIGURE 3.17 – WATER SUPPLY AND DEMAND DISTRIBUTIONS AND RESPECTIVE FAILURE PROBABILITY



Source: authors' elaboration

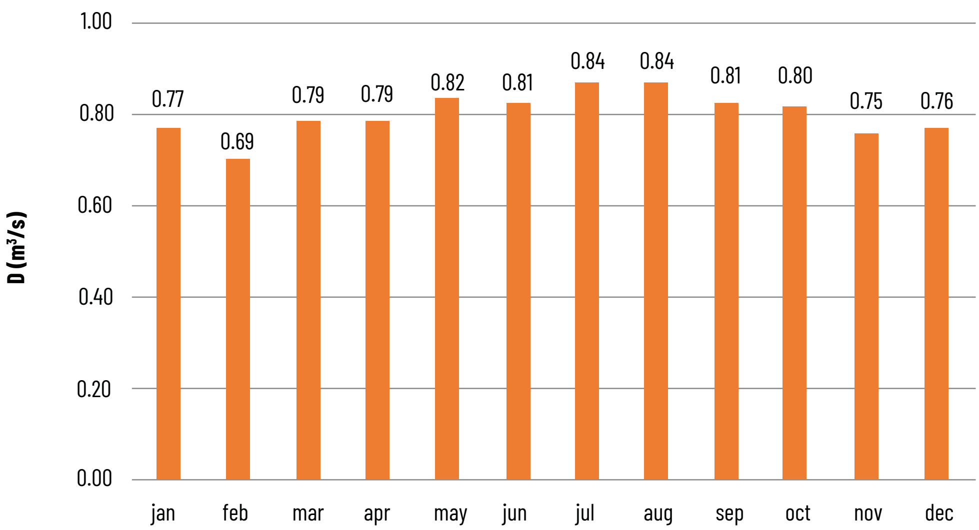
Water Demand in Future Scenarios

The assessment of future water demand in the Rodeador Basin was based on the water demand in the present situation (0.70 m^3/s), with an estimated increase of 12.7% in the year 2026 (UNESCO, 2017), resulting in a future water demand of 0.79 m^3/s.

Considering that the present basin water supply is 1.79 m^3/s, and that the demand of 0.79 m^3/s exceeds the upper threshold of the demand/supply ratio used by the National Water Resources Plan - *PNRH* (D/S = 0.4), 0.79 m^3/s was the water demand used to estimate all future scenarios.

After linearly applying the distribution of licensed monthly flow rates to the above-mentioned water demand, the effective monthly water demand was found for future scenarios (Figure 3.18).

FIGURE 3.18 – AVERAGE MONTHLY WATER DEMAND IN THE RIBEIRÃO BASIN, IN 2040 AND 2070



Source: authors' elaboration

RESULTS

Water Risk in the Rodeador Basin in Future Scenarios

The intra-annual water risk values in the Rodeador Basin, calculated through the probability of failure and using future projections of water supply and demand for the Basin, are presented in Table 3.49.

TABLE 3.49 – INTRA-ANNUAL WATER RISK IN THE RODEADOR BASIN IN 2040 AND 2070 USING FUTURE WATER SUPPLY AND DEMAND PROJECTIONS

MONTH	SUPPLY				DEMAND
	2040		2070		
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	
	------------ M³/S ------------				M³/S
Jan.	2.35	0.38	0.57	0.12	0.77
Feb.	2.17	0.35	0.53	0.11	0.69
Mar.	2.20	0.35	0.54	0.11	0.79
Apr.	1.83	0.30	0.45	0.09	0.79
May.	1.09	0.18	0.27	0.05	0.82
Jun.	0.77	0.12	0.19	0.04	0.81
Jul.	0.59	0.10	0.14	0.03	0.84
Aug.	0.47	0.08	0.11	0.02	0.84
Sep.	0.44	0.07	0.11	0.02	0.81
Oct.	0.59	0.09	0.14	0.03	0.80
Nov.	1.09	0.18	0.27	0.06	0.75
Dec.	1.89	0.30	0.46	0.10	0.76
Average	1.29	0.21	0.32	0.07	0.79
S.D.	0.74	0.12	0.18	0.04	0.04
$r_{O,D}$	-0.69	-0.68	-0.69	-0.72	-
WRI (p_f)	**25.9**	**100.0**	**98.7**	**100.0**	**-**

Source: authors' elaboration

The table above indicates that, in the RCP 4.5-2040 scenario, the water risk would be 25.9%, almost twice as much as the present scenario (15.3%). In the three other future scenarios, the water risk would be even higher (98.7% to 100%). In all future scenarios, the water risk for the Rodeador Basin would be unacceptable (>5%) (CHAVES; LORENA, 2019), thus requiring effective prevention and adaptation measures.

INTEGRATION OF WATER SUSTAINABILITY & WATER RISKS IN THE RODEADOR BASIN

The results of sustainability and water risk in the Rodeador Basin, in the different scenarios analyzed, are presented in an integrated manner in Table 3.50. This Table indicates that, as the *inter-annual* water sustainability decreases, the *intra-annual* water risk increases, and vice versa.

TABLE 3.50 – SUMMARY OF SUSTAINABILITY AND WATER RISK RESULTS IN THE RODEADOR BASIN, IN CURRENT AND FUTURE SCENARIOS

INDICATOR / SCENARIO	PRESENT	2040		2070	
		4.5	8.5	4.5	8.5
Water Sustainability	0.70	0.44	0.00	0.00	0.00
Water Risk	15.3%	25.9%	100.0%	98.7%	100.0%

Source: authors' elaboration

According to the Table above, three out of the five scenarios were below the lowest limit of water sustainability (0.2), and the limit of water risk (5%) was surpassed in all of the scenarios. These results indicate that prevention and adaptation measures are necessary in the basin, otherwise there will be serious socioeconomic and environmental consequences.

Although the scope of this study did not cover future water supply and demand scenarios in the Descoberto and Paranoá Basins, considering their WRSD results in the present scenario (Figure 3.13), it is very likely that their sustainability and water risk would also be considered inadmissible in these basins' future scenarios.

Furthermore, as water sustainability in the Rodeador Basin was negatively correlated to its water risk (Table 3.50), a similar trend of WRI increase is expected for the Descoberto and Paranoá Basins, since they are hydrologically similar.

4 ESTIMATE OF UNCERTAINTY

The projections of sustainability and water risk have uncertainties that can reduce the reliability of their results and, therefore, affect the decision-making process. The indexes used in this study present intrinsic and extrinsic uncertainties, which must be analyzed together with their results, in order to better guide users and decision-makers. In this Chapter, these sources of uncertainty and their respective impacts are analyzed.

INTEGRATED SUSTAINABILITY

Although official and quantitative data were dominantly used to estimate integrated sustainability in the Paranoá and Descoberto Basins, some of the data used were qualitative, such as the results of the surveys for managers and stakeholders.

This subjectivity in the qualitative WSI parameters contributes to the uncertainty in the results of the respective indicators and, consequently, in the index's final result. However, since the number of qualitative and subjective parameters was small, this uncertainty was reduced.

In the case of quantitative data, there are associated uncertainties, such as spatial and temporal variability, as well as measurement errors, which are inherent to the hydro-environmental and socioeconomic monitoring process.

However, due to the linear and additive structure of the WSI (equation 2.2), an eventual overestimation in one of the index's indicators would probably be compensated by an underestimation in another (CHAVES; ALÍPAZ, 2007), thus reducing the overall index uncertainty. This error reduction property is desirable in mathematical models (CHAVES; NEARING; 1991).

It is also worth noting that the results of the WSI for the Descoberto (0.66) and Paranoá (0.68) basins were similar. As the two Basins have similar physiographic, hydrological and socioeconomic characteristics, this is an indication that the estimation was accurate.

WATER SUSTAINABILITY

Considering that the water sustainability of the Paranoá, Descoberto and Rodeador river basins, calculated through the WRSD (equation 2.3), was based on the average water annual supply and demand, it is possible that these were over/underestimated in the study. However, since official water supply and demand data were used, the bias probability is reduced.

The eventual underestimation caused by unauthorized water use in the three basins was compensated by the overestimation represented by the assumption that all licensed volume is used.

As for water supply, the average affluent flows and reserved volumes, obtained from the historical series, are an unbiased estimator of water supply in the present condition. They represent the long-term behavior of water supply in the basins, but not their variability. However, considering the small standard deviation of the inter-annual water supply (Figures 3.7 and 3.9), large variations in water sustainability over the years are not expected.

Furthermore, the linear and additive structure of the WRSD (equation 2.3) allows for the compensation of eventual underestimation and overestimation in supply and demand, thus reducing estimation bias (CHAVES; NEARING, 1990).

WATER RISK

The uncertainties in the estimation of the Rodeador intra-annual water result from possible data error. In the case of the baseline analysis (present), the IWR used official average monthly water supply and demand data, which are unbiased estimators. In the case of water demand data, an eventual underestimation of unauthorized water use was compensated by an overestimation of the licensed water volumes, which are seldom used.

Although the water risk index (equation 2.8) has a non-linear structure, enhancing the potential of error propagation in the model, the incorporation of the temporal variability (monthly water supply and demand distributions) and the stochastic character of the index tend to reduce overall uncertainty.

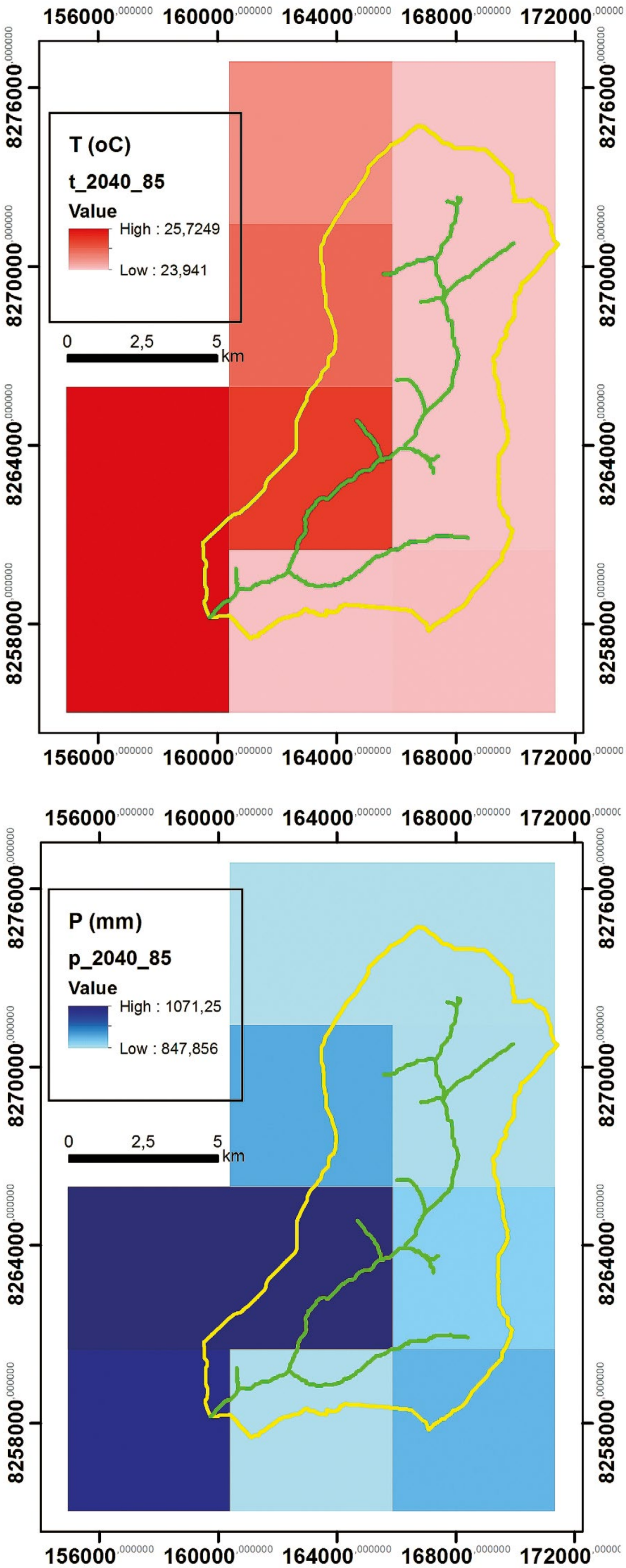
In the case of future climate and water demand scenarios, there are uncertainties associated with the GCM model projections, even after they have been locally applied, particularly in low latitudes (YOO; CHO; 2018). Furthermore, the use of P and T projections of a single GCM model (HadGEM2/Eta) may be biased (TEUTSCHBEIN; SEIBERT; 2012).

To assess this potential bias, annual P and T data from four other GCM models (BESM, CanESM2, HadGEM2 and MIROC5), regionalized by the Eta model (20km) in 2040 and 2070, were compared with HadGEM2 model (20km) P & T projections in the Rodeador Basin. A Mann-Wilcoxson test indicated that the ensemble P & T averages of the four 20km GCMs were statistically the same as the HadGEM2/Eta-5 km projection averages, indicating little bias in the latter.

Furthermore, the Gardner runoff model (equation 2.10) was validated through a comparison between the observed and the projected streamflow data in the period between 1990-2010, indicating that the model is reliable.

Eventual spatial uncertainties in climate projections were minimized through regionalization on 5x5 grid-cells (Figure 4.1), thus allowing the desired P & T spatial variability to be assessed at the basin level.

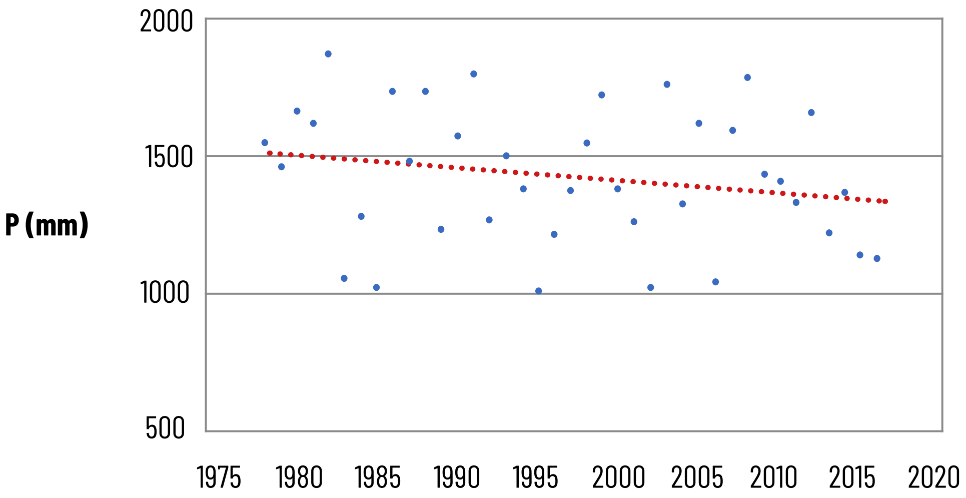
FIGURE 4.1 – P AND T PROJECTIONS OF THE HADGEM2/ETA (5 KM) MODEL FOR THE RODEADOR BASIN



Source: authors' elaboration

The drastic precipitation reduction in future scenarios, indicated by the projections of the HadGEM2/Eta model, is corroborated by evidence from the current historical series. Figure 4.2 shows the trend of reduced rainfall in the Federal District over the last 40 years.

FIGURE 4.2 – ANNUAL PRECIPITATION IN THE DESCOBERTO RIVER BASIN BETWEEN 1979 AND 2017



Source: authors' elaboration

5 RECOMMENDATIONS

The concerning results of integrated sustainability, of water sustainability, and water risk obtained regarding the Paranoá, Descoberto, and Rodeador Basins require effective prevention and adaptation measures. These measures are presented in the subchapters below.

INTEGRATED SUSTAINABILITY

Descoberto River Basin

There were six limiting parameters (scores ≤ 0.5) found in the WSI the Descoberto Basin, three of them were related to the Hydrology indicator, reflecting the basin low per capita water availability.

Those sustainability bottlenecks shall be prioritized in the form of actions and policies, so that the global basin sustainability can be improved in the future. These bottlenecks are presented and discussed below.

- In the case of the *Hydrology* indicator, its low score (0.46) derived from the high unit water demand, and from the demand increase between 2015 and 2018. To improve this indicator, demand management measures are recommended, including reducing water losses and adopting water reuse;
- Regarding the *Environment-Response* parameter (0.25), it could be improved by implementing new protected areas around the basin, such as APAs and parks, raising the parameter's score;
- The *Life-Response* parameter (0.5) could increase by improving the population's living conditions (income, education and life expectancy), as a result of regional development;
- In the case of the *Policy-Response* parameter (0.50), its improvement requires new investments in IWRM actions in the basin, such as stakeholder education, increased water use efficiency, erosion control, some of which are underway within the scope of the CITinova Project.

Paranoá River Basin

In the case of the Paranoá River Basin, four limiting factors contributed its reduced sustainability, namely:

- The low score of the Hydrology-State parameter (0.38), which is a result of a high unit water demand (D_a=1,394 inhab/hm^3.year), requires demand management actions, including loss control and water reuse;
- An improvement in the Environment-Response parameter (0.25) could be achieved with new protected areas in the Basin, such as APAs and parks;
- An increase in the Life-Response parameter (0.50) could be achieved with an improvement in the population's living conditions (income, education and life expectancy), as a result of regional socioeconomic development;
- In the case of the Policy-Response parameter (0.50), new investments in IWRM actions in the basin are necessary for its improvement, such as environmental education, increased water use efficiency, erosion control, some of which are already taking place within the scope of the CITinova Project.

WATER SUSTAINABILITY

As shown in Figure 3.13, the Rodeador and Paranoá Basins have a *medium* level of water sustainability, since their WRSD scores fell between 0.2 and 0.8. However, the Descoberto Basin's WRSD (0.32) comes close to the index lowest limit (0.2). The Descoberto reservoir failure, which resulted in the 2017 water crisis, is strong evidence of this vulnerability.

Hence, greater attention from managers and civil society is recommended, such as the adoption of appropriate adaptation measures. These include structural (construction projects) and non-structural (management) actions in order to increase water supply and reduce water demand in the basin.

The conclusion of the project to supply water from the Corumbá IV reservoir to the western region of the Federal District will relieve part of the current demand on the Descoberto System. In addition, the global demand for water can be reduced with educational campaigns to rationalize water use, and with financial incentives for water reuse.

Considering that part of the water demand of the Descoberto Basin is irrigation, and that the Rodeador conveyance channel has an earthen bottom, its lining could result in substantial water savings.

In addition, financial incentives, such as payments for environmental services, can be useful for the Descoberto Basin, allowing irrigators to increase their efficiency, thus replacing less efficient systems (gravity, furrows) with more efficient ones (micro-sprinkler, drip).

WATER RISK

Reducing the high intra-annual water risk in the Rodeador Basin, especially in future scenarios, requires great effort on the part of managers and civil society. Demand management measures, such as an increase in the irrigation efficiency and water tariffs could reduce demand and the intra-annual water risk in the Basin. However, these actions call for important changes in the behavior of water users, which can be achieved with educational campaigns and financial incentives.

Since similar high water risks are likely to incur in other unregulated basins of the Federal District, it is recommended that other water risk assessments be carried out to evaluate different management scenarios of water supply and demand.

In any case, in order to tackle future threats regarding water resources, despite the existence of uncertainties, the Precautionary Principle (KRIEBEL; 2001) must be observed and preventive management measures must be adopted, before the impacts occur.

ADAPTATION STRATEGIES

The adaptation strategies and measures aimed at increasing water sustainability and reducing water risk include projecting vulnerabilities, technical and economic feasibility, as well as available financial resources.

Adaptation measures include a mix of structural and non-structural actions, as well as economic and educational instruments, which must be applied in a cross-cutting and multi-sectoral manner. Among the non-structural adaptation mechanisms are (ECE, 2009):

- Legal and regulatory instruments;
- Economic and financial instruments;
- Educational and informative tools; and
- Governance instruments

In the case of economic instruments, the *economic costs* of climate impacts and risks for differing water uses must be carefully evaluated, so that the adaptation measures can be more effective.

Additionally, *preventive measures* should be prioritized (ECE, 2009), such as improving water use efficiency according to sectors and restoration and management of soil and water in Basin.

Measures to *increase resilience* include the genetic improvement of plants to reduce water consumption and changes in reservoir operation rules, in order to increase reservoir reliability.

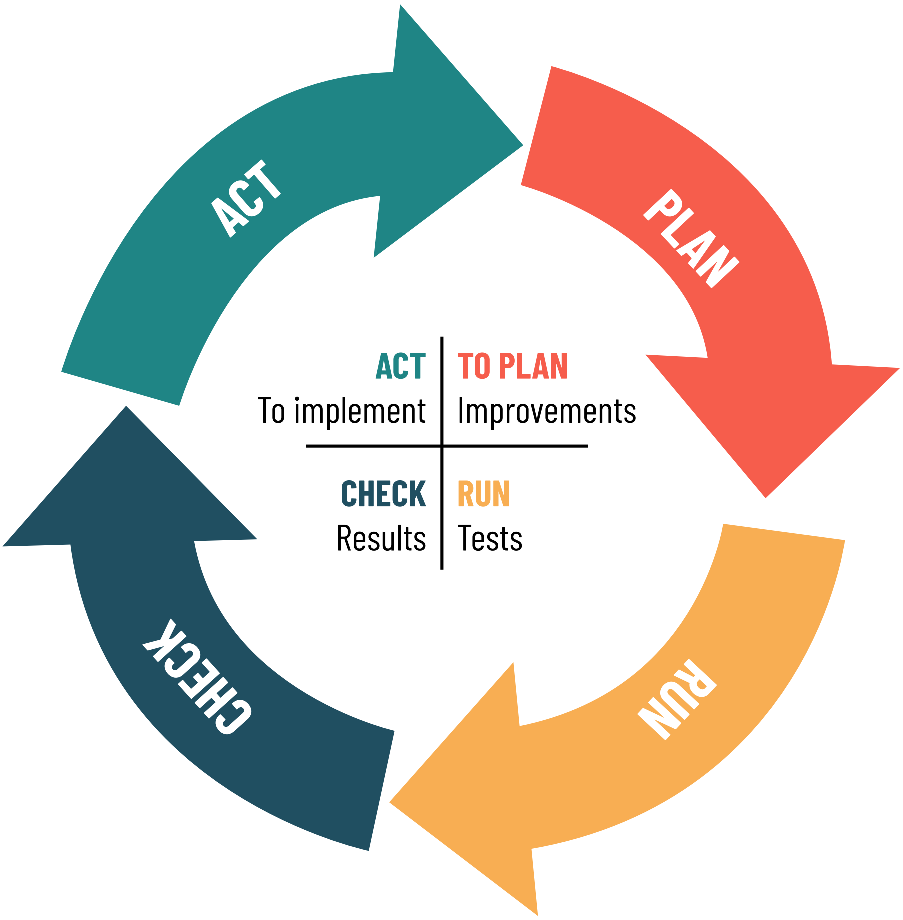
Preparedness measures can also be used to reduce the negative impacts of extreme events on water resources, including early warning systems, increased reservoir reliability, inter-basin transfers, demand management and technological innovations.

Additionally, response measures could be adopted to reduce the direct impacts of extreme events, including the development of alternative sources of water supply, preventive maintenance of waterworks, etc.

To be effective, the above-mentioned *adaptation measures* must be implemented over short, medium and long-term horizons. Initially, adaptation policies and measures must be evaluated with respect to their capacity to tackle current and future impacts (from climate change or increased demand), in order to reduce the vulnerability in the basins.

Additionally, alternative *adaptation measures* must be developed and compared with previous ones, following an adaptive management process (Figure 5.1). However, the selected adaptation measures must be duly approved at the political and socioeconomic levels, before their implementation, in order to increase their effectiveness.

FIGURE 5.1 – PDCA ADAPTATION PROCESS



Source: authors' elaboration

Finally, the adaptation strategy should be followed by an implementation plan, with detailed responsibilities and budgets (ECE, 2009). Considering the above, it is recommended that an appropriate adaptation study be prepared for the Rodeador Basin, considering the aforementioned aspects.

6 CONCLUSIONS

The main conclusions of this study, which assessed the water risk and sustainability of strategic basins of the Federal District, are:

- Integrated sustainability in the Descoberto River Basin, calculated using the WSI index, in the period between 2015 and 2018, scored 0.66, which is considered a medium level. The main bottlenecks were the high *per capita* water demand as well as societal response aspects;
- Integrated sustainability in the Paranoá River Basin, in the period between 2015 and 2018, scored 0.68 (medium). The main limiting factor was the insufficient response to the observed pressures;
- Water sustainability, calculated using the WRSD index, in the Descoberto, Paranoá and Rodeador Basins, in the present scenario, scored 0.32, 0.66, and 0.58 (medium);
- As the WSI and WRSD indexes are complementary in terms of sustainability assessment, the use of both indicators allowed for the assessment of the hydrological, socioeconomic, environmental and governance aspects of the basins studied, under present conditions;
- Because of the concerning results, it is recommended that the WSI and WRSD indexes be applied to the Descoberto and Paranoá Basins, for future scenarios;
- Water risk in the Rodeador Basin, which includes the *intra-annual* aspect of water supply in the current scenario, was 15.3%, exceeding the 5% threshold. Furthermore, in future GHG emission scenarios (RCP 4.5 and 8.5), in 2040 and 2070, water risk is expected to increase significantly, reaching 100% in the most severe cases;
- The sustainability (WRSD) and water risk (WRI) indexes, when applied to the Rodeador Basin, were inversely proportional and proved to be useful for estimating the basin's inter-annual and intra-annual water security, in different water supply and demand scenarios;
- The concerning future projections of water sustainability and water risk, in turn, require effective public actions and policies so as to tackle the predicted threats;
- Due to their importance and potential for replicability, the indexes applied in this study can be replicated in the other basins of the Federal District;
- Uncertainties regarding index results were minimized through official quantitative data. The few qualitative data used in the WSI were obtained from local managers, thus reducing uncertainty in the results;
- The highest uncertainties in the analysis resulted from climate projections from the GCMs, used in the future water risk index in the Rodeador Basin. However, the regionalization of climate data has reduced the potential bias;
- Finally, in order to face future threats to sustainability and water risk in the Rodeador Basin, adaptation measures and strategies were presented, following the state-of-the-art on the subject.

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APPENDIX

TABLE A1 – INDICATORES, PARAMETERS, NÍVEIS E ESCORES DO ÍNDICE DE SUSTENTABILIDADE DE BACIAS (ISB) PARA AS CONDIÇÕES DO DISTRITO FEDERAL (CHAVES; ALÍPAZ, 2007)

INDICATOR	PRESSURE			STATE			RESPONSE		
	PARAMETER	VALUE	ESCORE	PARAMETER	VALUE	ESCORE	PARAMETER	VALUE	ESCORE
Hydrology (H)	Variation in unit water demand (D_a) in the period analyzed	Δ > 20% 20% > Δ > 10% 10 > Δ > 0% 0 > Δ > -10% Δ < -10%	0.00 0.25 0.50 0.75 1.00	Long-term unit water demand in the D_a basin (inhabitant/hm³.yr)	D_a > 2000 2000 > D_a > 1000 1000 > D_a > 600 600 > D_a > 100 D_a < 100	0.00 0.25 0.50 0.75 1.00	Evolution in the efficiency of water use in the basin, in the period	Very Poor Poor Medium Good Excellent	0.00 0.25 0.50 0.75 1.00
	Variation of total P in the basin, in the period	Δ > 20% 20% > Δ > 10% 10 > Δ > 0% 0 > Δ > -10% Δ < -10%	0.00 0.25 0.50 0.75 1.00	Basin WQI (long term)	IQA < 25 25 < IQA < 50 50 < IQA < 70 70 < IQA < 90 IQA > 90	0.00 0.25 0.50 0.75 1.00	Variation in the WQI of the basin, in the period studied	Δ < -20% -20% <Δ< -10% -10% < Δ < 0% 0 < Δ < +10% Δ > 10%	0.00 0.25 0.50 0.75 1.00
Environment (E)	Environmental Pressure Index (EPI) of the basin, in the period	IPA > 20% 20% > IPA > 10% 10% > IPA > 5% 5% > IPA > 0% IPA < 0%	0.00 0.25 0.50 0.75 1.00	% of the basin with natural vegetation (NV)	VN < 5% 5% < VN< 10% 10% < VN< 25% 25% < VN< 40% VN > 40%	0.00 0.25 0.50 0.75 1.00	Evolution in the % of protected areas in the basin, in the period	Δ < -10% -10% < Δ < 0% 0% < Δ < 10% 10% < Δ < 20% Δ > 20%	0.00 0.25 0.50 0.75 1.00
Livelihood (L)	Variation of the HDI-Income of the basin, in the period	Δ < -20% -20% < Δ < -10% -10% < Δ < 0% 0 < Δ < +10% Δ > 10%	0.00 0.25 0.50 0.75 1.00	Basin weighted average HDI	IDH < 0.5 0.5 < IDH < 0.6 0.6 < IDH < 0.75 0.75 < IDH < 0.9 IDH > 0.9	0.00 0.25 0.50 0.75 1.00	Evolution of the basin's HDI in the period	Δ < -10% -10% < Δ < 0% 0% < Δ < 10% 10% < Δ < 20% Δ > 20%	0.00 0.25 0.50 0.75 1.00
Policy (P)	Variation of the HDI-Education of the basin, in the period	Δ < -20% -20% <Δ< -10% -10% < Δ < 0% 0 < Δ < +10% Δ > 10%	0.00 0.25 0.50 0.75 1.00	Legal and institutional capacity of the basin	Very bad Bad Medium Good Excellent	0.00 0.25 0.50 0.75 1.00	Evolution of spending on IWRM in the basin, in the period	Δ < -10% -10% < Δ < 0% 0% < Δ < 10% 10% < Δ < 20% Δ > 20%	0.00 0.25 0.50 0.75 1.00

Source: authors' elaboration

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