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RENATA LOCARNO FROTA

ANALYSIS OF WATER RESOURCES AS SOCIAL-NATURAL SYSTEM

FORTALEZA

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Dissertação apresentada ao Programa de Pós-Graduação em Engenharia Civil – Recursos Hídricos e Saneamento Ambiental da Universidade Federal do Ceará, como requisito parcial à obtenção do título de Mestre em Engenharia Civil. Área de concentração: Recursos Hídricos.

Orientador: Prof. Dr. Francisco de Assis Souza Filho.

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RENATA LOCARNO FROTA

ANALYSIS OF WATER RESOURCES AS SOCIAL-NATURAL SYSTEM

Dissertation presented to the Postgraduate Program in Water Resources and Environmental Sanitation of the Federal University of Ceará, as a partial requirement to obtain a Master's degree in Civil Engineering. Area of concentration: Water Resources.

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God.

My parentes, Potiguara and Rosina.

My brother, Victor.

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God guided me and helped me here.

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“A água faz parte do patrimônio do planeta. Cada continente, cada povo, cada cidadão, é plenamente responsável aos olhos de todos.”

(Declaração Universal do Direito da Água – ONU)

RESUMO

Os sistemas de recursos hídricos são compostos de elementos de dois ambientes distintos e inseparáveis: o ambiente físico, químico e biológico, e o ambiente cultural, sendo definidos como sistemas sócio-naturais. Portanto, para analisar as particularidades do sistema de recursos hídricos, é necessário reconhecer essas componentes, bem como suas interações, para garantir a segurança hídrica. Assim, o presente trabalho propõe a aplicação de técnicas prospectivas estratégicas para a análise de um sistema de recursos hídricos considerando os diversos componentes naturais, infra-estruturais, institucionais e socioeconômicos para contemplar sua complexidade e incerteza utilizando ferramentas matemáticas como o MicMac (Matriz de Impatos Cruzados - Multiplicações Aplicadas a uma Classificação), Teoria dos Gráficos e o software R. A abordagem MicMac foi utilizada para identificar os componentes socioeconômicos, as variáveis naturais e as relações existentes entre elas. Obteve-se a métrica e a divisão dos subsistemas, sendo capaz de identificar a estrutura e as inter-relações do sistema sócio-natural. As principais variáveis são: Eventos hidrológicos críticos (seca), Mudanças climáticas e Implementação institucional do SINGERH (Sistema Nacional de Gerenciamento de Recursos Hídricos). As variáveis centrais que receberam o maior número de conexões foram Abastecimento Humano e Conflitos de Uso da Água. Foi possível classificar o modelo em cinco subsistemas. Essas variáveis são incertezas críticas e delineam o futuro, por isso devem ser os elementos básicos dos estudos de prospectiva estratégica.

Palavras-Chave: Análise de Sistemas. Planejamento de Recursos Hídricos. Prospectiva Estratégica. Sistemas Sócio-naturais.

ABSTRACT

Water resources systems are composed of elements from two distinct and inseparable environments: the physical, chemical and biological environment, and the cultural environment, being defined as socio-natural systems. Therefore, in order to analyze the particularities of the water resources system, it is necessary to recognize these components as well as their interactions to guarantee water security. Thus, the present work proposes the application of strategic prospective techniques for the analysis of a water resources system considering the various natural, infrastructure, institutional and socioeconomic components in order to contemplate their complexity and uncertainty using mathematical tools, such as MicMac (Matrix of Cross-Impacts - Multiplications Applied to a Classification), Graph Theory and the software R. The MicMac approach was used to identify the socioeconomic components, natural variables and the relationships existing between them. It was obtained the metrics and the subsystems' division, being able to identify the structure and interrelations of the socio-natural system. The key variables are: Critical hydrological events (Drought), Climate change, and Institutional Implementation of SINGERH (Brazil's National Water Resources Management System). The central variables that received the largest number of connections were Human Supply and Water Use Conflicts. It was possible to classify the model into five subsystems. These variables are critical uncertainties and outline the future, so they should be the base elements of prospecting studies.

Keywords: Network Analysis. Socio-natural Systems. Strategic Prospective. Water Resources Planning.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANA	Agência Nacional das Águas
COGERH	Ceará Water Resources Management Company
SRH	Secretary of Water Resources
HEC	Hydrologic Engineering Center
IBGE	Brazilian Institute of Geography and Statistics
MICMAC	Matrix of Cross-Impacts - Multiplications Applied to a Classification
SINGERH	Brazil's National Water Resources Management System
SNA	Social Network Analysis
CPD	Conditional Probability Distribution
JPD	Joint Probability Distribution
GPD	Gross Domestic Product

SUMMARY

1 INTRODUCTION

1.1 Context

The uncertainty in the water supply due to changes in nature and gaps in the observations prompts the need for greater efficiency in the management of water resources. Modifications in the social, economic, political and institutional dynamics of society can interfere in in the demand for water, as well as changes in the physical environment, such as climate change, which are directly related to the water supply problem (ANA, 2016).

Thus, the planning of water resources in Brazil faces high uncertainty due to climatic and political-economic factors that impact water supply and demand. Water conservation, conflict resolution, vulnerability reduction, and pollution control are all extremely important items that should be included in this planning. It is the responsibility of water resource managers to ensure that the system is adaptable to a changing world, providing solutions to an uncertain future.

The water resources systems encompass components of two complexities: the biogeophysical environment and the cultural environment (social, political, economic and technological dimensions) (HAROU *et al.*, 2009; WHITE et al., 1992). They are characterized as self-referential and autopoietic by being able to operate on the basis of their own constituent operations, and by producing their own structure and all the elements that make it up. The political, economic and institutional aspects interfere on the management of water resources, affecting the ethical principles of equal water access, generating and intensifing conflicts for water uses. These characteristics make it difficult to use a purely mathematical theory for their comprehension and indicate the need to incorporate new approaches for system analysis in water resources planning.

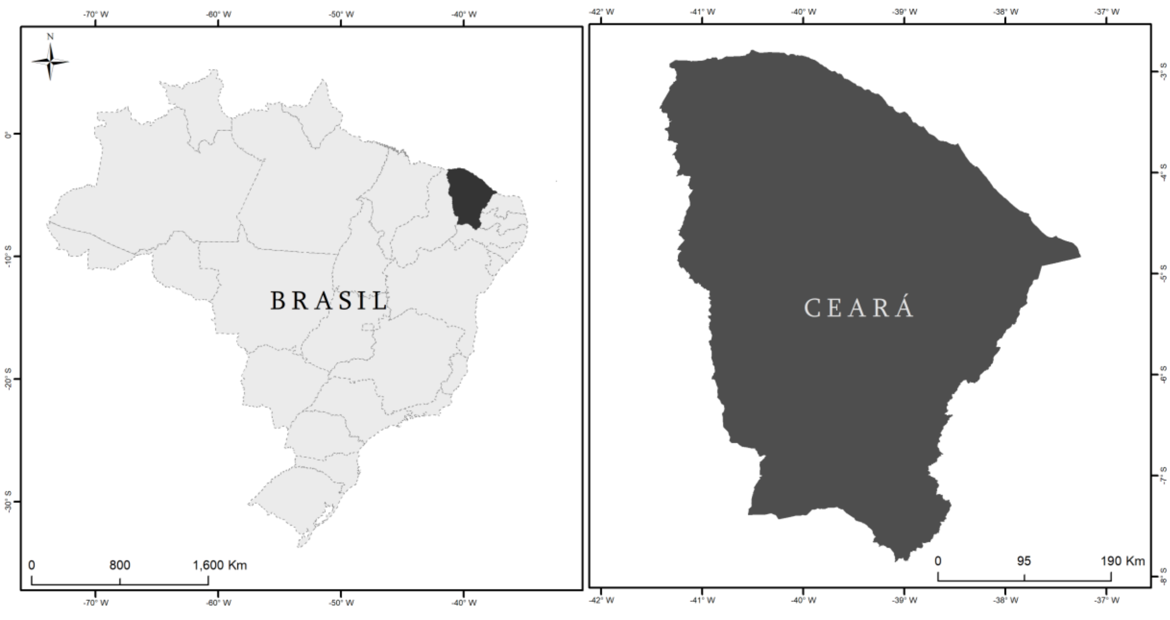
The initial approach to system analysis has become a mathematical and computational process, being later criticized by several researchers, such as Rogers & Fiering (1986), for being limited in social, political, and environmental representations (HAROU *et al.*, 2009). Consequently, they are difficult to be used in the understanding of water resources systems that are composed of elements from two distinct and inseparable environments: the physical, chemical and biological environment and the cultural environment, with social, political, economic and technological dimensions (WHITE *et al.*, 1992).

In this context, the study proposes to perform an analysis of the Water Resources System of Ceará using a strategic prospective methodology and Social Network Analysis (SNA) considering the natural, social, political, institutional and physical infrastructure components. The Micmac (Matrix of Cross-Impacts - Multiplications Applied to a Classification) method, developed by Michel Godet in 1994 (GODET, 1994), was used to assist the management of the water resources by providing scientific basis for the decision makers.

There are other methodologies to auxiliate in management decisions and in the implementation of strategic scenarios, such as General Electric; Schwartz and Global Business Network (GBN); Michael Porter, and his industrial scenarios; and Raul Grumbach. However, Micmac was used due to its strong power quantification, while the other methods are subjective (SOUSA, 2013).

The state of Ceará, is located in the northeastern region of Brazil, between 3º and 8º south latitude. The state has a predominant semi-arid climate in its territory, and it is known to face problems related to water scarcity (REIS, 2018). According to the IBGE 2010 census, this state has a population of more than 8 million inhabitants, high evaporation rates and great spatial variability of the rainfall regime.

Figure 1 – Location map of Ceará



Source:Author.

The management of water resources in Ceará is quite complex, as it is the scene of some local and interregional conflicts, which envolves the irrigated agriculture, livestock, aquaculture, industrial sector and human supply. The amount of water that is made available for a particular use can affect a different use and impact the economy of the sector.

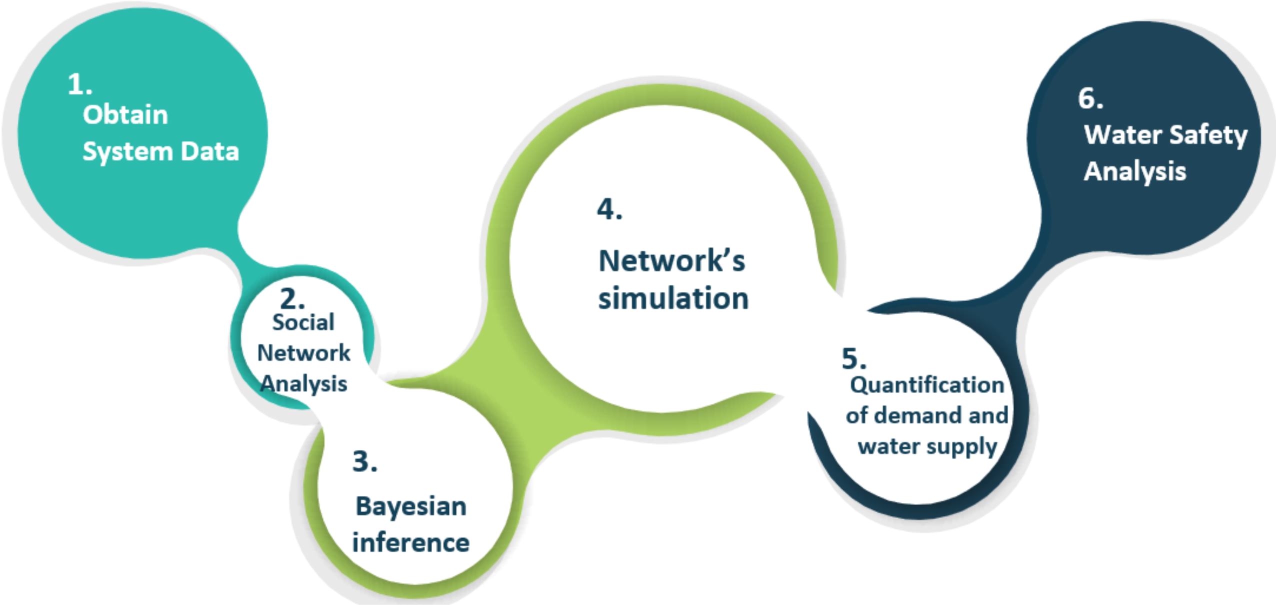
Another conflict is the integration of the Jaguaribe and Metropolitan basins and their water transfer, which means a dispute in the development of the territory, gaining visibility for the process of water allocation. There are still physical and operational restrictions of the system that must be taken into consideration in the region's water security. Therefore, in order to analyze the particularities of the water resources system, it is necessary to recognize the various components as well as their interactions to guarantee water security.

1.2 Objectives

The main objectives of this research are to analyse a water resources system, focusing on conflicts of water use, through the application of strategic prospective techniques and to identify the structure and interrelations of the socio-natural system, recognizing the socioeconomic and natural components, determining the relationships existing between them. Additionally, the present work aims to model the Water Resources System considering the same components through mathematical tools such as Social Network Analysis developed using free software R (R Development Core Team, 2005) and the researchers' interpretation. Lastly, it is expected to provide a technical and a scientific support to decision makers in order to assist the management of water resources.

As a recommendation for future work, we have proposed to develop and evaluate a scenario planning methodology for Water Resources Planning (focusing on Basin Plans and Water Safety Plans) considering the various natural, infrastructure, institutional and socioeconomic components pertinent to the water resources systems in order to contemplate the complexity and the uncertainty of the variables using Bayesian Inference and Graph Theory. Thus, six steps were created to achieve this metology, as illustrated in Figure 2. The work developed in this study allows us to reach step 2.

Figure 2 - Future work steps



Source: Author.

The specific objectives are:

- Find the most influential and dependents variables of the system;
- Find the key variables which are critical uncertainties and outline the future, so they should be the base elements of prospecting studies;
- Analysis of the graph from metrics, such as centrality, density, and centralization, in order to find the central variables;
- Clustering the variables in order to form subsystems;
- Perform final analysis of subsystems and other results obtained;
- Observe the behaviour of the water system under analysis;
- Introduce future work as an extension of this methodology;

1.3 Structure

This document is constituted of five chapters, where in the first chapter a contextualization of the study is made presenting and defining the expected objectives. The second and third chapters present the analysis, which are: Strategic prospective for the analysis of water resources systems and Analysis of water resources the social-natural system using graph theory. In the first one, MicMac and free software R were used as tools. In the second analysis, Social Network Analysis and free software R was used. The fourth chapter is a recommendation of future work. The dissertation is concluded in the fourth chapter with discussions about the research products, conclusions and recommendations of the study.

2 STRATEGIC PROSPECTIVE FOR THE ANALYSIS OF WATER RESOURCES SYSTEMS

2.1 Introduction

The planning of water resources is quite complex, because there is a high level of uncertainty due to climatic and political-economic factors which impact water supply and demand. It includes the search for water conservation, conflict resolution, vulnerability and risk reduction, pollution supervision and control. It is an ongoing process of decision-making and is based on systems analysis.

Systems analysis emerges from the General Systems Theory developed by the German biologist, Ludwig von Bertalanffy, as a structural-functional approach. The function of the system is related to what must be done so that the system and its structures are maintained (KICH *et al.*, 2010).

The application of systems analysis to water resources planning became more intense in 1956, at the Harvard Water Program of the Graduate School of Public Administration. This project aimed to optimize water resources systems through mathematical models and time series (MAASS *et al.*, 1962; GRIGG, 1996). The optimization techniques allowed the operation of the reservoirs in order to satisfy a set of previously defined criteria.

Wurbs (1993) states that a range of models was developed to evaluate the behavior of reservoir operations. These models used linear programming (LP), nonlinear programming and dynamic programming (DP). They often work best when combined, as we can observe in a real-time optimization study that was developed to determine the schedules of release reservoirs for the hydroelectric power generation in the California Central Valley Project (YEH, 1981). Chung and Helweg (1985) have associated PD with HEC-3 in an analysis of operational policies for Lake Oroville and the San Luis Reservoir.

According to Libanio (2017), in his research called “The experience of Brazil’s National Water Management Pact”, the results and impacts of Brazil’s national and subnational water policies are difficult to measure due to the lack of reliable and standardized information, which makes difficult to apply systems analysis.

Over the years, several softwares have been created to facilitate the analysis of systems, among which we can mention HEC, created by The Corps of Engineers' Hydrologic Engineering Center, which has several models, such as: SSARR, MITSIM, IRIS, TAMUWRAP, RSS, REZES, MODSIM, AQUANET, SIGA (MARSHALL, 1991; WURBS, 1993; BARROS, 2013).

The initial approach to system analysis has become a mathematical and computational process, being later criticized by several researchers, such as Rogers & Fiering (1986), for being limited in social, political, and environmental representations (HAROU *et al.*, 2009). Consequently, they are hard to be used in understanding water resources systems that are composed of elements from two distinct and inseparable environments: the physical, chemical and biological environment and the cultural environment, with social, political, economic and technological dimensions (WHITE *et al.*, 1992).

According to Kunzler (2004), the imported elements of the two environments are not ready and finished. Once an element is selected, it will be processed by the system according to the function it performs.

In this way, understanding the water resources systems means understanding a double complexity: one related to the environment, and the other, related to the system itself. It is necessary to understand also that systems should surpass the complexity of the environment, which constantly creates new unexpected possibilities, and leads to the need of evolving and changing its structures (KICH *et al.*, 2010).

According to White *et al.* (1992), water resources systems can then be termed as *socio-natural systems*. According to Luhmann (2011), social systems are self-referential and autopoietic. Self-referential because they are "capable of operating on the basis of their own constituent operations" (p.78), and autopoietic, because they are their own structures and all the elements that make it up (p.89). These characteristics preclude the use of a purely mathematical theory for their understanding.

The difficulties and concepts presented point to the need of incorporating new systems analysis approaches in water resources planning.

In this context, this article proposes to analyse the water resources system of the state of Ceará through strategic prospective. In order to do this, the Micmac (Matrix Multiplication applied to a classification) method, developed by Michel Godet in 1994, will be used.

The Micmac allows to identify the components of the system and its key variables, i.e.

variables which influence the whole system and are the main candidates for prospective studies.

The Micmac approach allows the identification of socioeconomic and natural variables by identifying the existing relationships between them, thus identifying the structure and interrelations of the socio-natural system. This representation allows the identification of key variables and the construction of consistent scenarios for water resources planning.

This methodology was carried out for the State of Ceará, located in the Northeast region of Brazil, which has a population of more than 8 million people, according to the IBGE 2010 census. According to Ordinance No. 05, dated October 10, 2002, Ceará has 148,826 km² of territory, and according to the update of the geographic and social map of the Brazilian Semi-arid (carried out by the Ministry of National Integration in 2005), 86.82% of this area is characterized as semi-arid, with high evaporation rates and great spatial variability of the rainfall regime.

2.1.1 Strategic Prospective

Strategic prospective became part of the planning of many organizations in order to reduce the uncertainties of the future, as some authors describe: Porter (1989), Godet (2000), Marcial and Grumbach (2008), and Schwartz (2000).

According to Sousa (2013), it is one of the most appropriate tools for defining strategies in uncertain environments. The philosopher Gaston Berger, in 1957, used the term prospective for the first time, based on the Latin verb *prospicere* that means "to look away" (MARCIAL & GRUMBACH, 2008). Later, Michel Godet used the same word to explain his prospective methodology.

Abdoli *et al.* (2017) used the prospective strategy associated with the Micmac method to draw up a development plan for the province of Bushehr, Iran, an area of extreme importance to the oil and gas industry. The study identified 30 factors of great importance, and later created 4 scenarios on a horizon until 2025.

Surahman *et al.* (2018) have employed the strategic perspective and the construction of scenarios to identify the most influential and dependent variables in an Indonesian agricultural production system, to allow the short-term agricultural use of degraded peatlands in a relatively sustainable way.

When it comes to the water resources area, there are two outstanding experiences of prospective studies, namely: the World Water Council in 2000, and the United Nations Environment Program (UNEP) in 2003. Both studies aimed the development of sustainable actions in relation to water resources, and therefore, prospective scenarios were elaborated. These works were internationally relevant because they mobilized several people to elaborate the prospective scenarios (Nascimento *et al.*, 2010).

According to Marcial and Grumbach (2008), the prospective scenarios are combinations of variables that describe several possible futures and their links with the present. In addition, these studies are one of the most qualified tools to delineate strategies in situations of uncertainty and risk, although they do not propose to end uncertainties, but rather, to reduce them (BRANDALISE *et al.*, 2012; SOUSA, 2013).

2.2 Methodology

For the development of this study, a bibliographic survey was initially carried out, to collect variables that characterized the water resources system of the state of Ceará. These variables were used in the elaboration of a structural matrix. Subsequently, this matrix was submitted to stakeholders involved in the water resources management in Ceará. The obtained information was then analyzed, for the further elaboration of the influence-dependence diagram. The steps of applying the Micmac method are described below:

2.2.1 Survey of the variables that characterize the water resources system.

At this stage, an exploratory research was carried out, composed of a bibliographical survey and dialogues with technicians of the Ceará Water Resources Management Company (COGERH), in order to identify the variables that characterized the assessed water resources system.

2.2.2 Description of the relationship between variables

To describe the relationship between the variables that characterize the water resources system, a square matrix, called “Structural Analysis Matrix”, was elaborated, in which the variables were related by multiple crosses, as shown in Table 1.

Table 1- Structural analysis matrix model

Variables	Var1	Var2	Var3
Var1			
Var2			
Var3			

Source:Author.

A workshop was organized, when the Micmac method was presented to all participants (stakeholders in the management of water resources of Ceará, i.e. technicians, scientists and water users).

The filling of the matrix was carried out by the participants, after the explanation of the definition of each matrix variable. For each pair of variables, the stakeholders gave their opinions on the existence or not of direct relation between them, using the following indexes:

- (0) Has no influence;
- (1) Weak influence;
- (2) Average influence;
- (3) Strong influence; and
- (4) Potential influence.

Next, the most influential and system-dependent variable was evaluated. This influence was given by the sum of the indices in each row of the square matrix, while the dependency was represented by the sum of the indices in each column.

The matrix can also be analyzed considering the direct and indirect influences. Direct influence occurs when one variable directly affects another and vice versa. The indirect influence exists when one variable affects another in a way that this affects a third variable, so that the first variable has indirect influence over the and third one, i.e. there is a hidden variable which, in some cases, can greatly affect the result, being necessary then to raise the matrix to a power. In this study, the focus was only on the direct matrix (GODET, 1994).

The potential classification (index 4) means that one variable has currently little influence over another but will have strong influence in the future (GODET, 1994). Therefore, when the classification is non-potential, what has been classified as 4 becomes zero, and when it is potential, 4 becomes 3. In this study, the potential classification was used.

2.2.3 Identification of key variables

The key variables were identified through the *influence-dependence diagram*, represented by the X-axis (the dependence), and the Y-axis (the influence), comprising four quadrants, each representing a variable profile:

- *Quadrant 1* – This quadrant exhibits the input variables, which govern future events. They are at the same time very influential and little dependent;
- *Quadrant 2* – Shows the relay variables. These exert a high influence on the system, but are also very dependent, generating instability in the system;
- *Quadrant 3* – Presents the result variables, whose performance depends on the input variables; and
- *Quadrant 4* – displays the excluded/platoon variables, which have no or very little influence in the system and can be eliminated.

The dependence influence diagram was constructed using the free software R.

2.3 Results

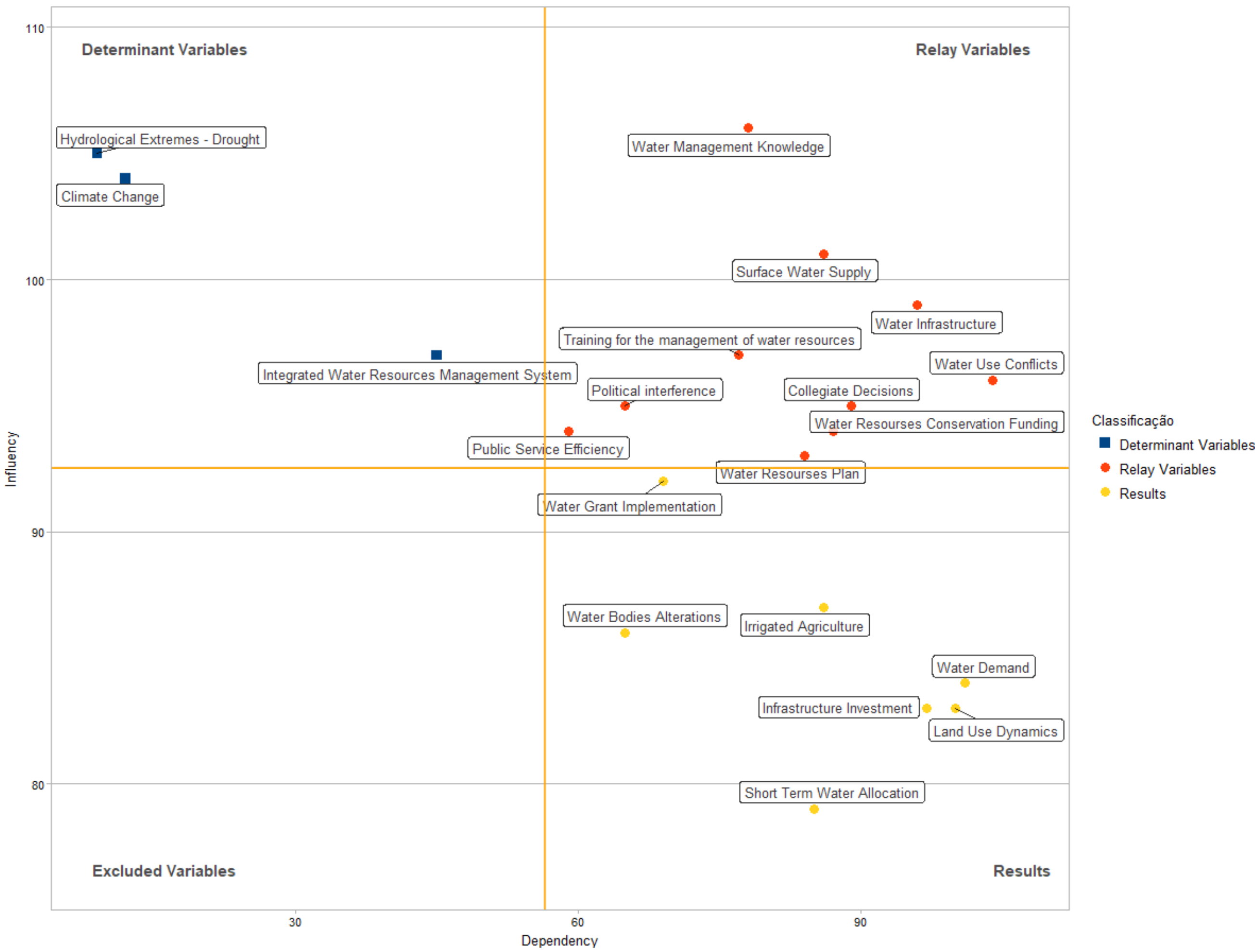
The list of variables that characterize the system, present in Annex A, was obtained from the Prospecting study in *Universo das Águas* by Nascimento *et al.* (2010). This list comprised 47 variables, such as: biome conservation, aquaculture, water infrastructure and hydrological extremes.

The matrix had 47 rows and columns and was filled out by 6 technicians of the Ceará Water Resources Management Company (COGERH), and 3 experts in the area of water resources in the state. A small example is shown in Annex B.

From the structural analysis matrices, a potential median matrix was created. This was evaluated through the MICMAC method using the software R (R Development Core Team, 2005). This matrix was used for the construction of the Influence-Dependence Diagram.

After the initial application of the MICMAC method, we selected the twenty variables that had the greatest influence and set up a new Influence-Dependence diagram, shown in Figure 1. The values of dependence and influence can be seen in Table 2.

Figure 3 - Influence-Dependence Diagram



Source:Author.

Table 2 - Influence and Dependence values of each variable

	Variables	Influence	Dependence
1	Water Management Knowledge	106	78
2	Hydrological Extremes – Drought	105	9
3	Climate Change	104	12
4	Surface Water Supply	101	86
5	Infrastructure Investment	99	96
6	Integrated Water Resources Management System	97	45
7	Training for the management of water resources	97	77
8	Water Use Conflicts	96	104
9	Collegiate Decisions	95	89
10	Political interference	95	65
11	Water Resources Conservation Funding	94	87
12	Public Service Efficiency	94	59
13	Water Resources Plan	93	84
14	Water Grant Implementation	92	69
15	Irrigated Agriculture	87	86
16	Water Bodies Alterations	86	65
17	Water Demand	84	101
18	Land Use Dynamics	83	100
19	Infrastructure Investment	83	97
20	Short Term Water Allocation	79	85

Source: Author.

The most influential variable was “Water Management Knowledge” and the most dependent variable was “Water Use Conflicts”. We also observed that the variable “Surface Water Supply” had a strong influence on the variable “Irrigated Agriculture”, and that the variable “Investment in Infrastructure” was very dependent of the variable “Training for the Management of Water Resources”. It is noteworthy that, considering that there were 47 variables in total, it was impracticable to report all relationships between them in this work.

The Influence-Dependence diagram is shown in Figure 1. It was observed that 50% of the variables were relay-type and caused instability to the system, due to its high dependence and influence on the other variables. Also, 35% were strongly determined by the input- and relay-type variables, they were called result-type variables, and 3% were high-motricity and low-dependency variables, they are responsible for the future events.

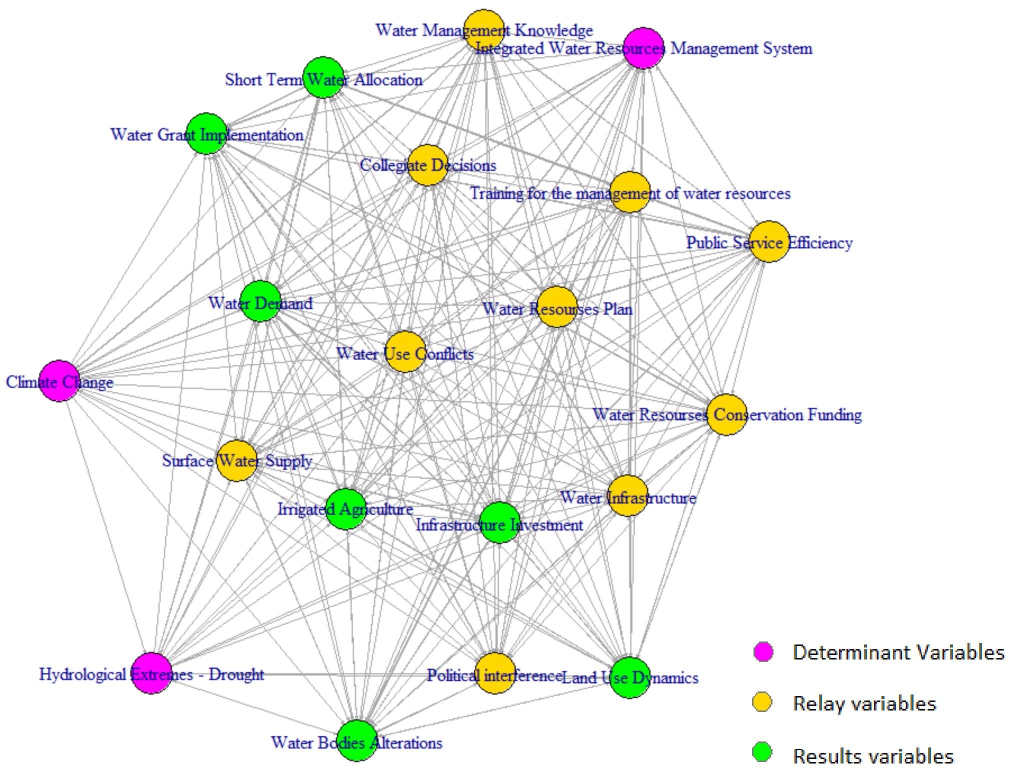
Through the diagram in Figure 1, it was possible to identify three key variables: (i)

Critical hydrological events – Drought; (ii) Climate change; and (iii) Institutional Implementation of SINGERH. These were in the first quadrant, being therefore the ones with the highest motricity, that is, those that govern the future events, and consequently, are of greater support for the system in prospective scenarios.

The distribution of the variables in the diagram should also be considered, because if it is L-shaped, the diagram is characterized as stable, otherwise it is unstable (GODET, 2000). In this study, the diagram was considered to be unstable, for it had many variables with a lot of concomitant influence and dependence, and any action on them would impact and change another variable.

Figure 2 shows a graph of interrelationships between the variables. It is distributed as follows: the input and excluded variables are at the bottom, and the relay and output variables are interconnected in the center. As in this example, we did not present excluded variables, so only the input variables can be observed at the extremities. These bind the relay- and result-type variables, according to their influence on each other. The link and result variables are also interconnected.

Figure 4 - Graph of interrelations between variables



Source: Author.

2.4 Conclusion

The analysis performed in this study, through the application of the Micmac method, is a way to reflect on the behavior of the water system and to identify structural variables, in evaluating its influence and dependence.

The key variables of the system were identified: Critical hydrological events (Drought), Climate change, and Institutional Implementation of SINGERH. These variables were those with the highest influence and lowest dependency in the system and should be the main focus of prospective studies regarding Ceará water resources system.

Droughts have historically marked Ceará and climate change has been the subject of several discussions at a global level. Managing river basins is a difficult and not always possible task. These three variables are critical uncertainties; thus, they outline the future and should be the base elements of prospecting studies.

The variables identified come from the environment to which Ceará water resources system is inserted. Thus, they are able to promote its adaptation and restructuring, if considered in planning processes.

A similar method, social network analysis, was explored by Ogada *et al.* (2017), which used influence/interest plot and network diagram to analyze stakeholders' social and structural characteristics in Lake Naivasha basin, Kenya. In this paper, we did determine hydrological variables.

The development of this study faced difficulties due to the logistics of applying the matrix, because the financial resources were scarce. Therefore, it is recommended that the study be applied to a greater number of stakeholders in water resources management in Ceará.

In addition, it is suggested that in future studies the development of prospective scenarios be performed based on the key variables identified in this present analysis. This methodology allows to delineate future actions and measures, if these key variables disturb the system.

3 ANALYSIS OF WATER RESOURCES AS SOCIAL-NATURAL SYSTEM USING GRAPH THEORY

3.1 Introduction

Adapting to the variations in the water supply and water demand patterns becomes an increasingly complex challenge. Modifications in the social, economic, political and institutional dynamics of society can interfere in the changes in the demand for water, as well as variations in the physical environment, such as climate change, are directly related to the water supply problem. It is the responsibility of water resource managers to ensure the adaptability of the system to a changing world, providing solutions to an uncertain future (ANA, 2016).

The social systems are self-referential - they are “able to operate based on their own constituent operations” - and autopoietic - they produce their own structure and its elements. These characteristics preclude the use of a purely mathematical theory for their understanding (LUHMANN, 2011). Water resources systems can then be classified as socio-natural systems (WHITE *et al.*, 1992).

In order to analyze the nuances of a water resources system, considering the methodological weaknesses of the systems analysis, it is necessary to recognize the various social, natural and physical infrastructure components of a water system, as well as their interactions. For this, after selecting the variables of the Water Resources System of the State of Ceará, will be used Social Network Analysis to evaluate its components and subsystems.

Conflicts over water use play an important role as they directly impact the state's economy. These conflicts are composed of different variables such as irrigated agriculture, livestock, aquaculture, industrial sector and human supply. Prioritizing one of these uses impacts another sector, then this decision must be taken very carefully.

In addition, it can be observed that there are subsystems, composed of economic, political, quantitative groups, among others. Each of these have a role in the system and changing one component can change all the system’s behavior.

In this way, the study aims to model the Water Resources System considering the natural, social, political, institutional and physical infrastructure components using graph theory based on the structural matrix elaborated in the previous chapter. It is intended to find the most important variables for the operation of the system, in order to assist the management of water resources by providing technical and scientific background to decision makers.

The free software R was used to facilitate the analysis of the graph although it is indispensable the interpretation of the researchers.

3.1.1 Social Network Analysis (SNA)

Social Network Analysis was initially called "web" to emphasize the ease and flexibility of its structure. It is the study of social relations among a set of actors. More specifically, Prell & Bodin (2011) report that a social network consists of a set of relationships that apply to a set of social actors, as well as any additional information about these actors and relationships. According to Marteleto (2001), the individual attributes are not analyzed, instead the relations of the individuals with each other is the focus of analysis. Thus, the behaviors of the individuals depend on the structures that are inserted.

They are analyzed through mathematical and sociological approaches, where often their interpretation is carried out by the researcher. Therefore, it intends to go beyond the visualization of social relations and to make an analysis of the structural and social implications (SCOTT, 2017).

SNA can be used in a variety of fields, such as observing the behavior of students at a school, observing cycles of friendships, analyzing business negotiations, studying behaviors, and so on. Therefore, we can observe his vast employment in various fields.

SNA has tools that allow the study of metrics that provide a local (actor level) and global (network level) description of the network, graphical visualization, and community detection (Combe, Largeron, Egyed-Zsigmond & Géry, 2010; & Hastak, 2018).

Kim & Hastak (2018), applied social network analysis (SNA) to understand how social media networks spread information during emergency responses in 2016 Louisiana flood.

Ongkowijoyo (2018), proposed a model using tools of the network analysis aiming to draw and simulate the risk impact propagation in water supply of Surabaya, a city in Indonesia, developing a risk network map based on community perspective. The study aims to help decision makers in their actions.

3.1.2 Graph Theory

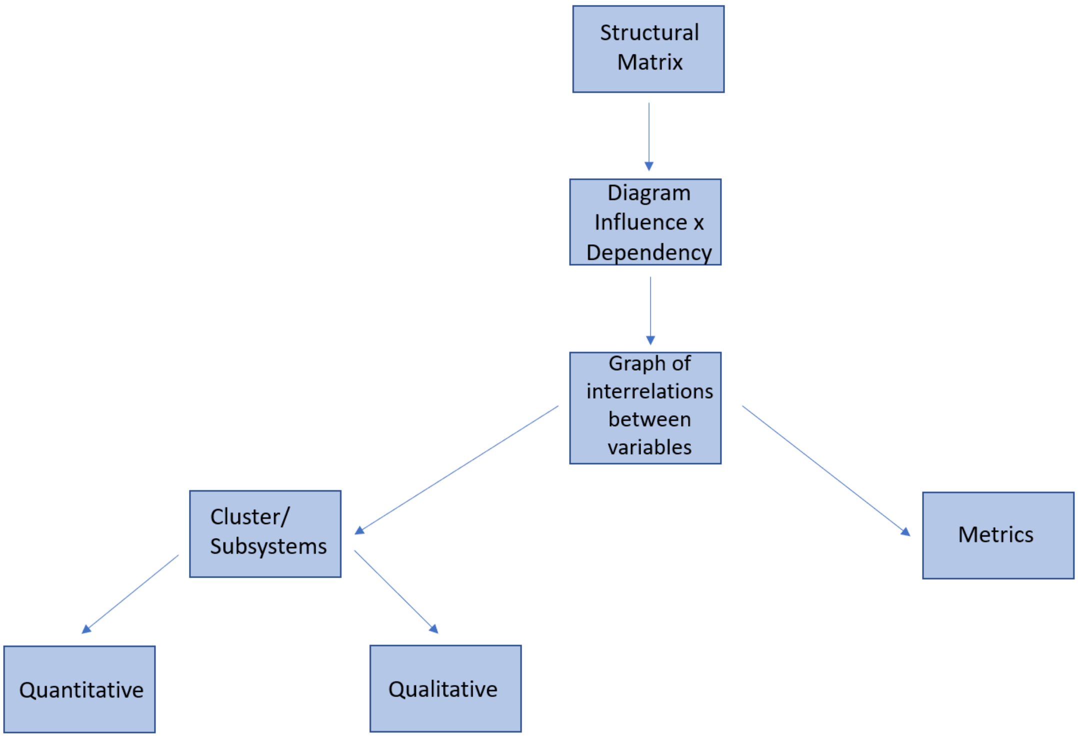
The Graph Theory began with the mathematician Leonhard Euler in 1736. Euler developed the basis of the theory that gave rise to the studies of the graphs when he published a work on the resolution of the problem of the seven bridges of Königsberg that consisted of crossing all the bridges without repeating them (GABARDO, 2015).

According to Scott (2017), graphs are points connected by paths, where points represent individuals, their goals, actions while the paths represent the causal interaction, and its consequences, connecting them and forming a relationship of interdependence. Thus, it will be formed groups or classes of points that have similar behaviors among themselves. The determination of the groups and their limits is not simple. It is often up to the researcher to adopt the methods.

3.2 Methodology

This work intends to analyze the components of the Water Resources System of the State of Ceará through the variables initially proposed in Strategic Prospective for the Analysis of Water Resources Systems. The steps of the methodology are presented in Figure 3.

Figure 5 - Methodology Scheme



Source: Author.

For the development of the study, a bibliographical survey was first carried out with technicians from the Water Resources Management Company of the state of Ceará in order to identify the variables that characterize the Water Resources System of the State of Ceará. We selected 47 variables that were used in the elaboration of a structural matrix that described the relation of each of them to each other through multiple crossings.

The fulfillment of the matrix was carried out by actors involved in the management of water resources in Ceará - technicians, scientists and users of water. To do so, a workshop was held in which the MicMac method was explained and the definition of each matrix variable was presented.

The matrix was filled according to the levels of influence, classified from 0 to 4, in order to construct the influence-dependence diagram of the variables. It is possible to evaluate the most dependent and influential variables of the System, as well as the key variables.

Then, using the free software R, we selected the variables with strong influence (3), totaling 32 variables, and constructed the graph of their interrelationships. We considered direct influences, which occurs when one variable directly affects another and vice versa, and potential, where future influences will be employed.

From the structural matrix and the influence and dependence diagram, the graph was constructed. It is a mathematical representation of the connections between vertices and edges that allow to visualize in a simplified way the present connections between vertices. In this approach the individuals, groups, or variables are represented by points (vertices) and their relations by lines (edges). In the layout obtained as a result, the input and excluded variables are at the ends and the link and output variables are interconnected in the center. As none of the analyzed variables were classified as excluded, only the input variables were positioned at the extremities. The relay and result variables are also interconnected.

Then a mathematical analysis called graph theory will be done and the interpretation of its information considering the components of the System. The free software R and the igraph package (Csárdi & Nepusz, 2006) will be used to obtain the metrics, which are the measures of diameter, reciprocity, transitivity, centrality, density and, centralization.

The first property is the diameter. It is the largest geodesic distance of the graph, that is, the longest path between the vertices. Next, we have the reciprocity, which in a directed graph shows which variables have mutual links.

Transitivity, on the other hand, measures the probability that adjacent vertices are connected. It is also called a clustering or agglomeration coefficient and can be local or global, respectively from a vertex or from the network.

Then comes the centrality. This is the measure of importance of a vertex in a graph. In this study, we used degree centrality, closeness centrality, centrality of intermediation, and eigenvector centrality.

In mathematical terms, the degree k_i of a vertex i is expressed by Equation 1:

$$k_i = \sum_{j=1}^{n} A_{ij} \quad (1)$$

Bavelas (1948) proposed that a message originating in the most central position of a network spreads throughout the network in minimal time. Thus, centrality is measured by observing the actors who have the least distance in relation to other actors are seen as having the greatest centrality of proximity. This emphasizes the independence of the actors, in which an actor close to others in a network tends not to depend on many intermediaries in the network (Freeman, 1979). This is the concept of closeness centrality and it can be given by Equation 2:

$$Cc = \frac{n-1}{\sum_{j=1}^{n} d(i,j)} \qquad (2)$$

Where C_c is the closeness centrality value, n is the number of vertices, $\sum_{j=1}^{n}$ is the sum of all distances for all vertices, and d (i, j) is the number of shortest paths connecting vertices i and j.

Betweenness centrality quantifies the number of times a node acts as a bridge along the shortest path between two other nodes. Thus, the closer to zero, nothing changes in the network if the node is removed. It can be calculated by Equation 3:

$$C_B(p_k) = \sum_{i<j} b_{ij}(p_k) \qquad (3)$$

Where C_b is the betweenness centrality value of a point pk, we sum its partial betweenness values for all unordered pairs of points where i # j # k and n is the number of points in the graph.

The Eigenvector centrality is a measure of the influence of a node in a network, in which the higher importance have high scores. It is calculated using Equation 4:

$$x_i = \frac{1}{\lambda} \sum_{j=1}^{n} A_{ij} x_j \qquad (4)$$

If we denote the centrality of vertex i by xi, then we can allow for this effect by making x_i proportional to the average of the centralities of i's network neighbours where λ is a constant. Defining the vector of centralities x = (x1,x2,...), we can rewrite this equation in matrix form as and hence we see that x is an eigenvector of the adjacency matrix with eigenvalue λ. The rewrite formula is shown in Equation (5):

$$\lambda x = Ax \qquad (5)$$

Finally, the properties that denote the cohesion of the system are density and centering.

Density is defined by the ratio between the number of communication links observed in a network and the maximum number of possible links (De Laat *et al.*, 2007). Scott (2017) states that in directed graphs the matrix is asymmetric, that is, a line from A to B may not be reciprocal. Thus, the density formula is described in Equation 6:

$$\rho = \frac{m}{n(n-1)} \tag{6}$$

However, degree centralization calculates how much only one actor is monopolizing the ties of the network. According to Freeman (1979), one can calculate the centralization by Equation 7, where $C_x(p_i)$ is the measure of a central point any i and $C_x(p_*)$ is the largest measure of the network.

$$C_x = \frac{\sum_{j=1}^{N} C_x(p_*) - C_x(p_i)}{max \sum_{j=1}^{N} C_x(p_*) - C_x(p_i)} \tag{7}$$

Clusters will also be obtained for the classification of the network into subsystems. This classification will be made quantitatively and qualitatively. The first one is achieved through the free software R that used an algorithm based on the greedy optimization of the quantity known as modularity, which counts the clicks to be grouped in subgroups, this formed three subsystems. According to Clauset (2004), modularity is a property that divides the network into communities. It measures how good the division is, or how far apart the different vertex types are from each other using a Q parameter, represented in Equation 8:

$$Q = \frac{1}{2m} * (\sum_{ij} (Aij - \frac{ki * kj}{2m})) * \delta(ci, cj) \tag{8}$$

In this equation, *m* is the number of edges, *Aij* is the element of the *A* adjacency matrix in row *i* and column *j*, *ki* is the degree of *i*, *kj* is the degree of *j*, *ci* is the type (or component) of *i*, *cj* that of *j*, the sum goes over all *i* and *j* pairs of vertices, and *delta(x,y)* is 1 if *x*=*y* and 0 otherwise.

The qualitative analysis will be through the analysis of specialists. It will be made by the common characteristics of the points are observed and it is grouped in two new subsystems, totalizing five subsystems.

Network analysis data can be obtained in three different ways. Survey research, observational research and document research. This study merges the three types, since after obtaining the variables through documents and observation, a research was done with professionals of the area to answer the structural matrix.

3.3 Results

This section describes the application and the analyses of the methodology in the case of study of the water resources management system of Ceará

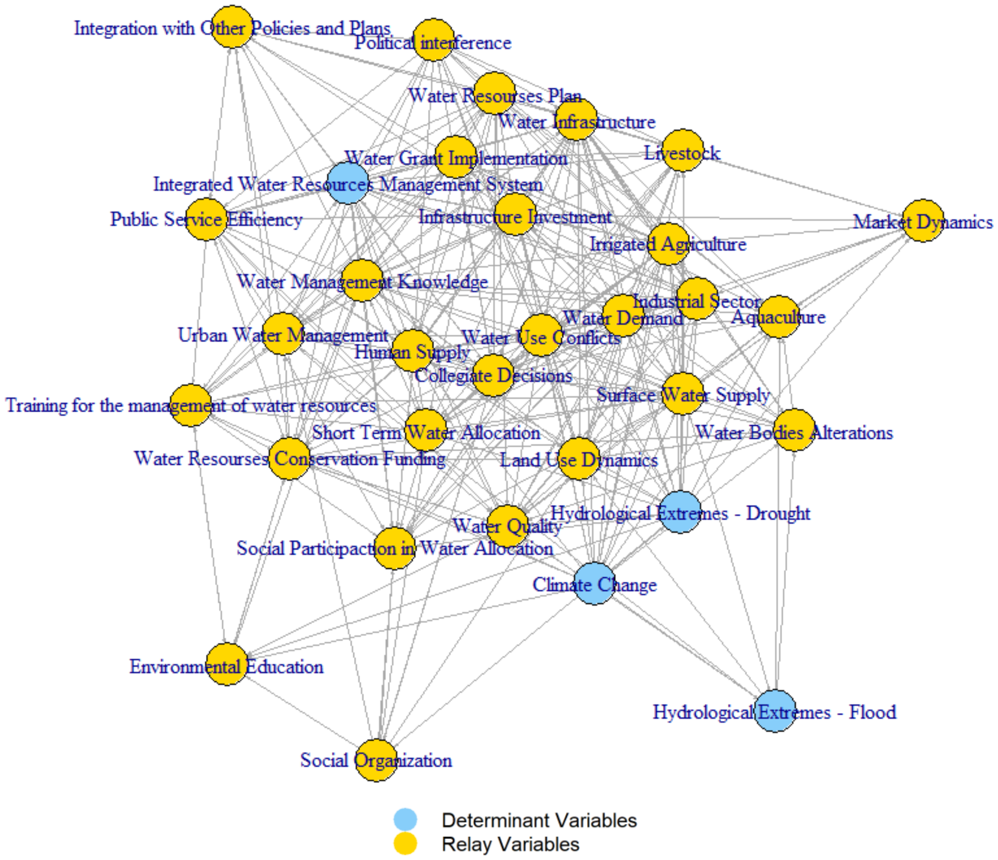
The study reveals the interrelationships of variables with strong influence in order to obtain the central variables and, therefore, considered important for the system. Through them, one can identify the main conflicts and treat them before the problem becomes irreversible, aiding the planning of water resources.

The results will be presented in three parts: Definition of the representative graph of the Water Resources System; Evaluation Metrics of the Water Resources System and Identification of Subsystems.

3.3.1. Definition of the representative graph of the Water Resources System

The identification of the relevant variables and their interconnections was performed with the aid of a graph. You can define a graph by vertices, or nodes, connected by means of edges. Thus, determined by G (V, E), where G is the graph, V are the vertices and E, the edges. The graph in analysis has order or number of vertices equal to 32, that is, it presents 32 variables. Its size is represented by the number of edges, so it has 340 connections, becoming a graph G (32,340), as it can be observed in Figure 4.

Figure 6 - Study Network



Source: Author.

The edges can present a direction through a flow of information in which one variable influences/names another, or the senders and receivers, where these are actors that name and those, the nominees. There are also reciprocal or mutual ones when one names the other and vice versa (PRELL & BODIN, 2011). Therefore, graphs are classified as directed or "digraphs", not directed and mixed. Edges can also have weights that mean costs. In this study the graph is considered acyclic directed because it has no cycles and its edges have a direction. And it was considered the same weight for all of them.

3.3.2. Evaluation Metrics of the Water Resources System

The analysis of the variables in the water resources system was performed based on its interrelation with the other variables. This evaluation was performed using the following metrics:

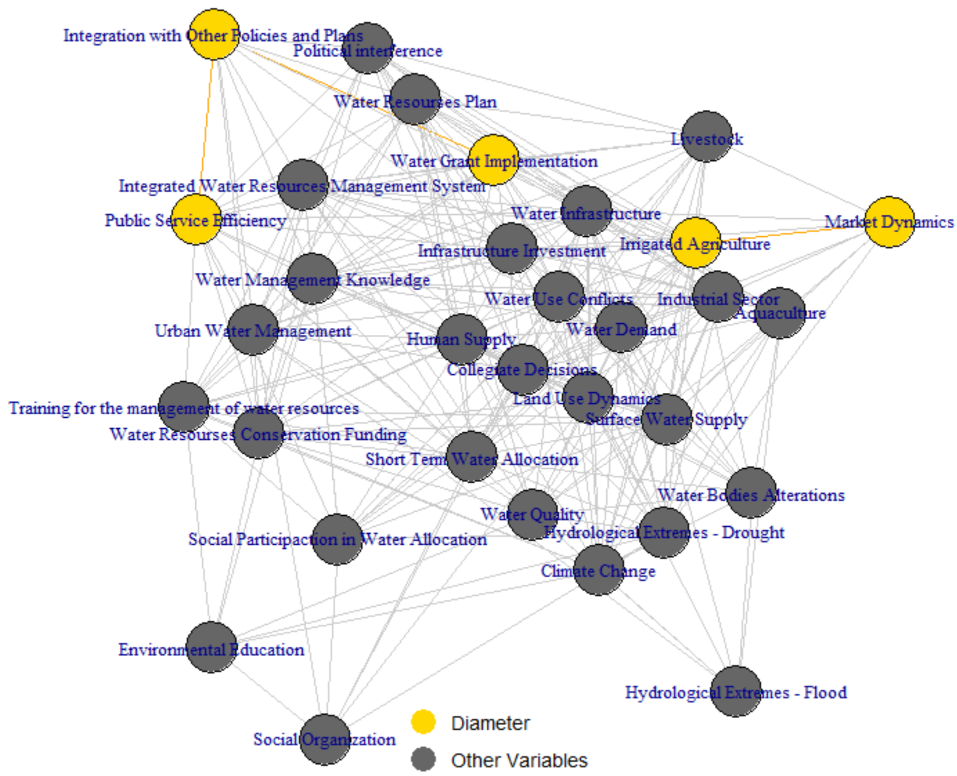
diameter, reciprocity, transitivity, centrality, density, and centralization.

3.3.2.1 Diameter

The Figure 7 represents the two most distant vertices: "Market dynamics" and "Public Sector Efficiency". The figure illustrates the longest path between them: "Integration with Other Policies and Plans", "Wate Grant Implementation" and "Irrigated Agriculture".

It can be observed that the diameter is relatively small, since the connection between two variables has at most three intermediaries, that is, the system is very interconnected, and the information transfer is fast.

Figure 7 – Diameter of the graph



Source: Author.

3.3.2.2 Reciprocity

The measure of reciprocity is defined by the propensity of mutual connections in a directed graph. We obtained a value of 0.447. It means that almost half of the variables are connected to the variables by which they already receive a connection. We observed that the variables have an intense feedback.

3.3.2.3 Transitivity

Transitivity is claimed to be a function of the strength of ties and it can be global or local. For directed graph, the direction of the arcs should be ignored. The global clustering coefficient is designed to provide an overview of the clustering in the network, since the local clustering coefficient provides an indication of the insertion of individual nodes.

Granovetter (1977) give us an example of this metric. With increasing size of the group considered the rationale for transitivity weakens. If P chooses O and O chooses X, P should choose X out of consistency; but if P does not know or barely knows X, nonchoice implies no inconsistency. For the logic of transitivity to apply, a group must be small enough so that any person knows enough about every other person to be able to decide whether to "choose" him and encounters him often enough that he feels the need for such a decision.

In this study, the global transitivity has a value of 0.60 and the higher this value, the more redundancy of connections exists in the network. The local transitivity is shown for each vertex in Table 3. It represents the ability of a vertex and its neighbor to form a subgroup.

Note that the global value is the highest of all local values, this is when the global value is considered between the triangles and the triples connected in the graph, while the locus is the ratio between the triangles connected to the vertex and the triples centered in the vertex.

Vertices with high degree have a larger probability to be connected with large degree vertices. This property is referred to in physics and social sciences as assortative mixing. In contrast, the disassortative mixing, in the sense that high-degree vertices have a majority of neighbors with low degree, whereas the opposite holds for low-degree vertices (NEWMAN, 2002; BARRAT, 2002).

Table 3 - Local Transitivity

VARIABLE	LOCAL TRANSITIVITY
Water Quality	0,3593
Surface Water Supply	0,3103
Water Bodies Alterations	0,4191
Hydrological Extremes – Drought	0,5052
Hydrological Extremes – Flood	0,5357
Land Use Dynamics	0,4329
Human Supply	0,3730
Social Organization	0,2222
Water Demand	0,3423
Irrigated Agriculture	0,2645
Industrial Sector	0,3320
Aquaculture	0,3464
Livestock	0,5441
Infrastructure Investment	0,4380
Urban Water Management	0,4444
Water Resourses Plan	0,5052
Short Term Water Allocation	0,3596
Social Participaction in Water Allocation	0,3567
Water Grant Implementation	0,3952
Climate Change	0,5810
Collegiate Decisions	0,2487
Political interference	0,5904
Environmental Education	0,1818
Integrated Water Resources Management System	0,4166
Water Resourses Conservation Funding	0,3116
Training for the management of water resources	0,3725
Water Use Conflicts	0,2369
Market Dynamics	0,3330

Public Service Efficiency	0,4000
Water Management Knowledge	0,2923
Integration with Other Policies and Plans	0,4065
Water Infrastructure	0,2691

Source: Author.

3.3.2.4 Centrality

The next property is called centrality. The word centrality refers to importance, power, prestige and popularity and in this study, it does not differ from this, since it is the measure of importance of a vertex in a graph. When a given vertex has a greater number of links compared to others, it can be said that it is central in the network. There are four centrality measures that are widely used in network analysis: Degree centrality, Betweenness centrality, Closeness centrality, and Eigenvector centrality.

Two points connected by an edge are called adjacents. Thus, the total of interconnected points in the neighborhood is called a degree, that is, it measures how many that point is adjacent. The number of connections of a vertex is called connectivity or degree. You can find the connections that arrive at a certain point (degree in) and that leave this same vertex (degree out). This can also be called degree centrality, which informs the immediate contacts that a particular actor has in the network. One vertex with many incoming links can be considered popular and others having many leaving, influence (PRELL & BODIN, 2011). The indegree is obtained by means of the sum of the columns of the structural matrix, the one used to classificate the levels of influence, while the the outdegree, by the sum of the lines. Table 4 shows these results. The average degree of the network is 21.25 and is obtained by summing the degrees of all vertices by their number.

Table 4 – Centrality degree

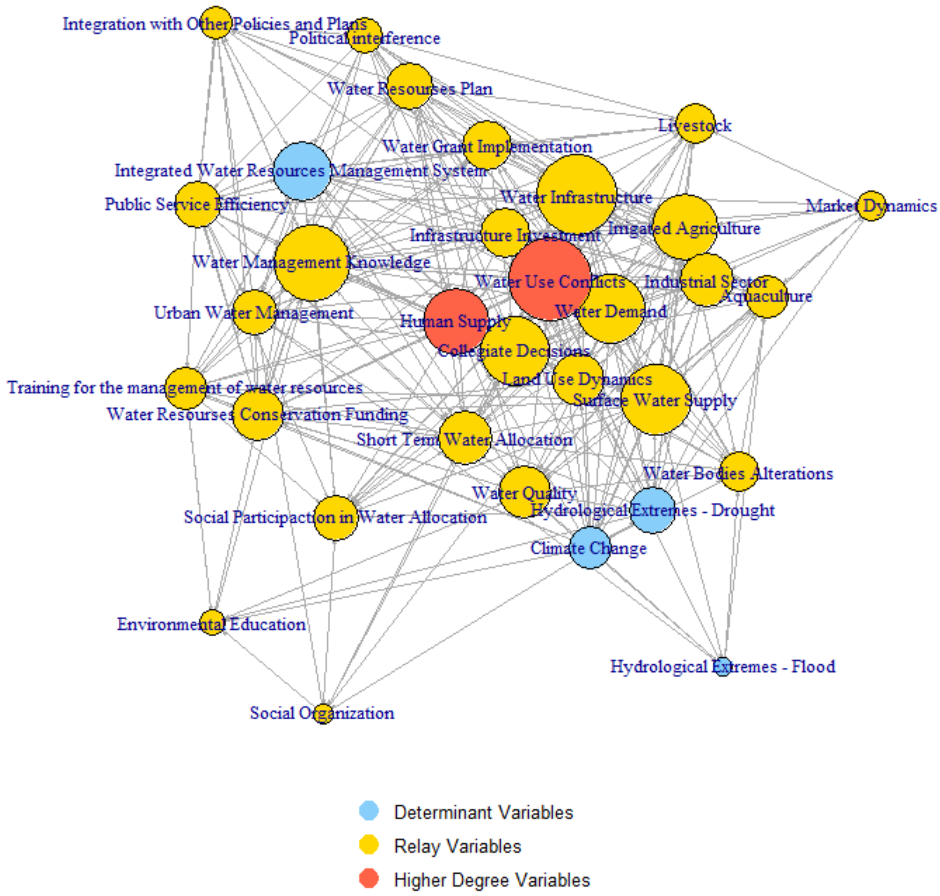
VARIABLE	DEGREE	DEGREE IN	DEGREE OUT
Water Quality	22	15	7
Surface Water Supply	30	15	15
Water Bodies Alterations	17	7	10

Hydrological Extremes – Drought	20	2	18
Hydrological Extremes – Flood	8	2	6
Land Use Dynamics	22	15	7
Human Supply	28	22	6
Social Organization	9	3	6
Water Demand	29	19	10
Irrigated Agriculture	28	15	13
Industrial Sector	23	13	10
Aquaculture	18	15	3
Livestock	17	12	5
Infrastructure Investment	21	17	4
Urban Water Management	19	13	6
Water Resourses Plan	20	8	12
Short Term Water Allocation	23	14	9
Social Participaction in Water Allocation	19	13	6
Water Grant Implementation	21	8	13
Climate Change	18	1	17
Collegiate Decisions	29	13	16
Political interference	15	2	13
Environmental Education	11	7	4
Integrated Water Resources Management System	25	5	20
Water Resourses Conservation Funding	22	11	11
Training for the management of water resources	18	6	12
Water Use Conflicts	35	20	15
Market Dynamics	13	6	7
Public Service Efficiency	20	5	15
Water Management Knowledge	32	11	21
Integration with Other Policies and Plans	14	6	8
Water Infrastructure	34	19	15

Source: Author.

The Figure 8 shows the size of the nodes according to the number of degrees of the variables. We can see that "Human Supply" and "Water Use Conflicts", in orange, have the highest number of incidental connections, so they have the greatest number of factors influencing it. "Water Management Knowledge", "Water Use Conflicts" and "Water Infrastructure" are considered the most popular variables because they have the highest total number of degrees. While "Integrated Water Resources Management System" and "Water Management Knowledge" are the most influential because they have the largest number of connections coming out of them, so a change in these variables can act strongly on the rest of the system. It is necessary to observe that comparisons can only be made between graphs that have the same size, because the degree of a point highly depends on the size of the graph.

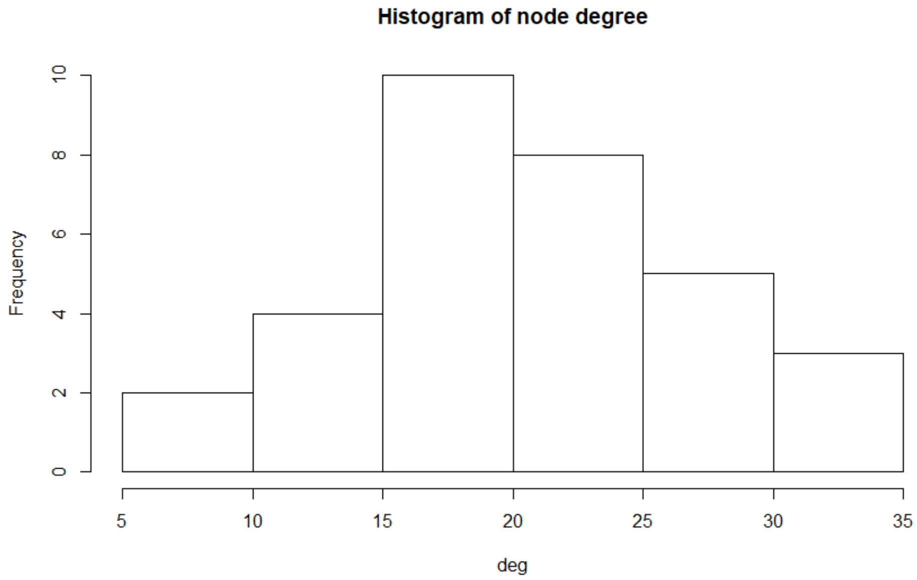
Figure 8 - Number of degrees of the variables



Source: Author.

The degree distribution or histogram, identified in Figure 9, is the number of vertices with a certain degree. In this study the graph presented a bell shape.

Figure 9 - Histogram

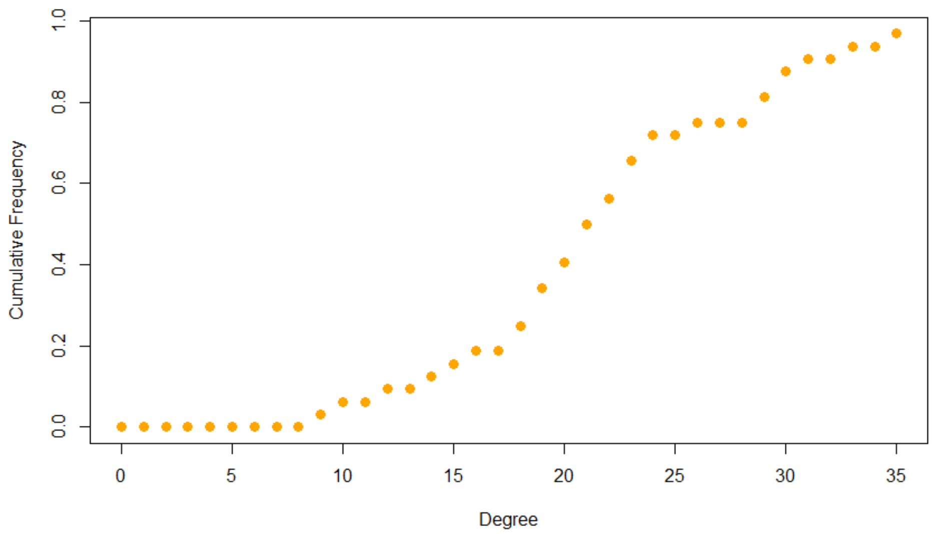


Source: Author.

It was observed that the maximum number of connections is 35 and its range 30-35 contains 3 variables, which are "Water Use Conflicts", "Water Infrastructure" and "Water Management Knowledge". Thus, the three listed above, they have many direct contacts, also called well connected.

In addition, Figure 10 shows the degree distribution graph. Where the x-axis is represented by the degree and the y-axis by the cumulative frequency. We can see that the minimum degree is 8.

Figure 10 - Degree Distribution



Source: Author.

The Table 5 summarizes the values of closeness centrality, betweenness centrality and eigenvector centrality for each variable.

It was observed that "Water Use Conflicts" obtained value 1, that is, it is the most important variable of the system, followed by "Human Supply".

Table 5 - Centralities

VARIABLE	CLOSENESS CENTRALITY	BETWEENNESS CENTRALITY	EIGENVECTOR CENTRALITY
Water Quality	0,0227	32,25	0,4946
Surface Water Supply	0,0250	90,96	0,6335
Water Bodies Alterations	0,0204	4,84	0,3145
Hydrological Extremes – Drought	0,0233	4,67	0,06751
Hydrological Extremes – Flood	0,0182	0,63	0,06751
Land Use Dynamics	0,0233	17,28	0,5738
Human Supply	0,0250	22,72	0,97
Social Organization	0,0181	3,89	0,1417
Water Demand	0,0244	38,78	0,93689
Irrigated Agriculture	0,0233	30,86	0,6416
Industrial Sector	0,0222	46,80	0,5916
Aquaculture	0,0212	6,16	0,5742

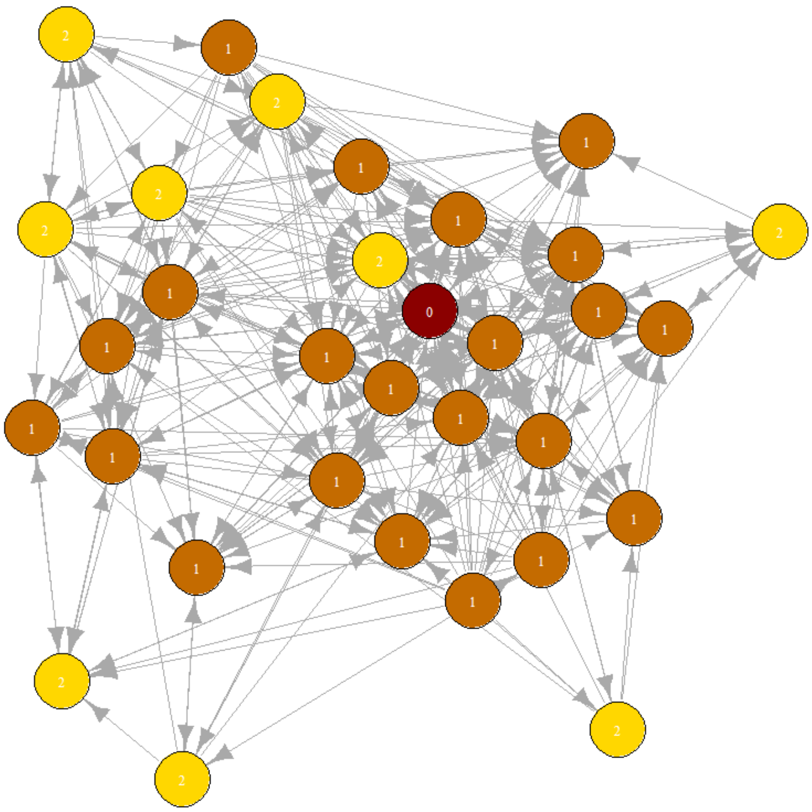
Livestock	0,0217	4,27	0,4886
Infrastructure Investment	0,0227	4,35	0,635
Urban Water Management	0,0222	12,49	0,4623
Water Resourses Plan	0,0227	7,39	0,297
Short Term Water Allocation	0,0222	21,49	0,617
Social Participaction in Water Allocation	0,0208	16,68	0,6129
Water Grant Implementation	0,0222	12,65	0,3344
Climate Change	0,0227	8,37	0,0577
Collegiate Decisions	0,0227	85,09	0,7709
Political interference	0,0213	3,47	0,097
Environmental Education	0,0180	8,32	0,162
Integrated Water Resources Management System	0,0244	13,01	0,1306
Water Resourses Conservation Funding	0,0217	42,16	0,3699
Training for the management of water resources	0,0208	12,17	0,121
Water Use Conflicts	0,0250	84,27	1
Market Dynamics	0,0189	7,78	0,3306
Public Service Efficiency	0,0217	7,59	0,1202
Water Management Knowledge	0,0256	58,36	0,4055
Integration with Other Policies and Plans	0,0192	19,84	0,2275
Water Infrastructure	0,0256	63,25	0,8768

Source: Author.

Points with less centrality are considered peripheral points, so they are loosely connected into the network.

Figure 11 shows how far are the remaining variables in relation to the most central variable “Water Use Conflicts”.

Figure 11 - How many nodes the other variables are in relation to Water Use Conflicts



Source: Author.

3.3.2.5 Density e Centralization

Density is defined by the ratio between the number of communication links observed in a network and the maximum number of possible links (De Laat *et al.*, 2007). The maximum number of potential connections is obtained by the combination according to Equation 9.

$$C = \binom{32}{2} \tag{9}$$

Where it was obtained 496 connections, but as it is a directed graph, the connections must be multiplied by two, as they arrive and leave the variables. Totaling 992 potential leads.

The graph can be considered a dense graph, where the number of edges is close to the maximum number of edges, otherwise it will be a sparse graph. The density obtained in software R resulted in 0.343 and the graph is considered sparse. We have the impression that the graph is cohesive because it has many points, but the number of links that could be exploited is much greater.

The centralization calculates how much only one actor is monopolizing the ties of the network. As the density, this value varies from 0 to 1, being the maximum value that where all loops are arranged on an actor and the minimum value that where all the actors have the same number of loops.

Thus, in this study the value of centralization is 0.37, being the point called "Water Use Conflicts" the structural center of the graph, that is, the pivot of the system.

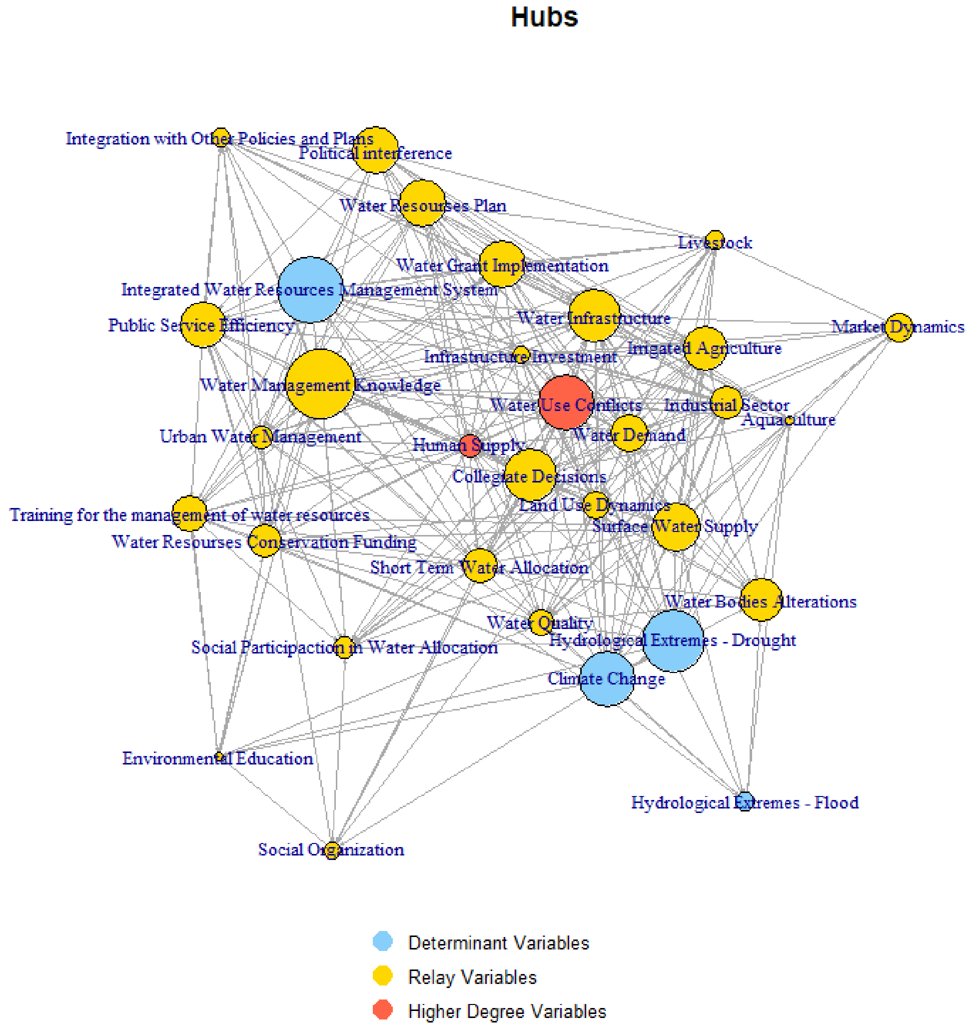
3.3.2.6 Hubs and Authorities

In directed networks we can usually identify two types of important vertices: hubs and authorities. They are central nodes highly connected and distributing information. The hubs and authorities are a refinement of input and output degrees: in the case of input degree we only count incoming lines while for authorities it is important also from whom the lines are coming (important or less important vertices); the same holds for hubs and output degree.

They could be called a mutually reinforcing relationship: a good hub is a page that points to many good authorities; a good authority is a page that is pointed to by many good hubs (KLEINBERG, 1999).

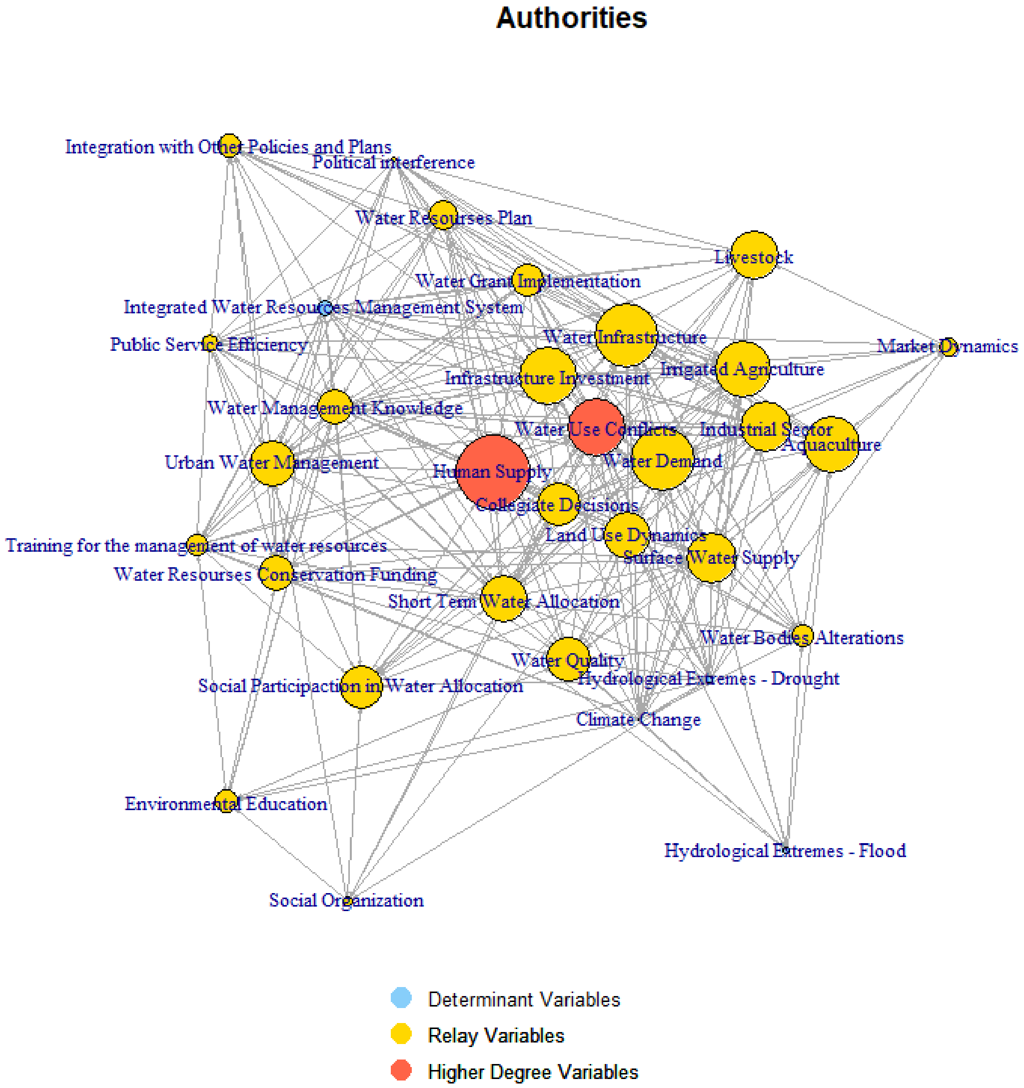
In Figures 12 and 13 we are able to get a perspective of hubs and authorities, respecttively.

Figure 12 - Hubs



Source: Author.

Figure 13 – Authorities



Source: Author.

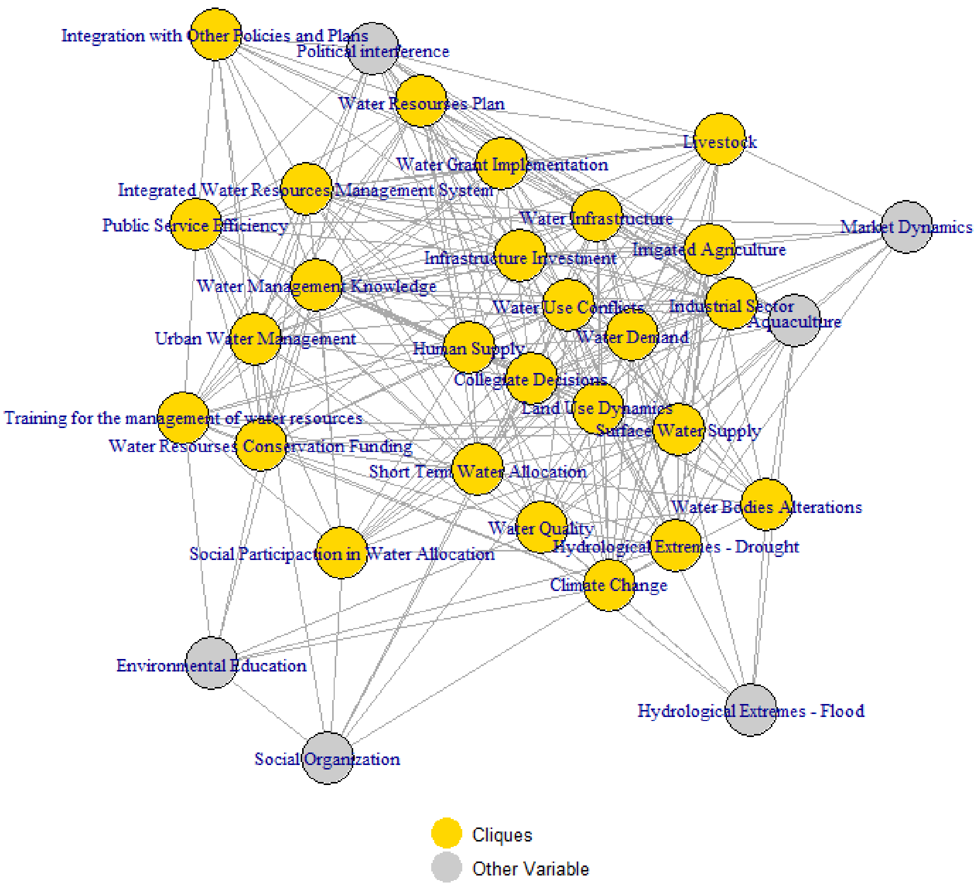
3.3.2.7 Graph analysis in unguided or non-directional form

From this point it is necessary to transform the graph in non-directional, because the direction of the connection does not matter, only the existence of it.

Click is a subset of its vertices such that every two vertices of the subset are connected by one edge. All members of the group must have mutual ties with each other. One can think of a click as a "fully related" set of vertices of a graph.

In Figure 14 the yellow circles are the clicks and the greys are out of the clicks. Because it is a dense graph, it is difficult to observe the direct connections.

Figure 14 - Clicks



Source: Author.

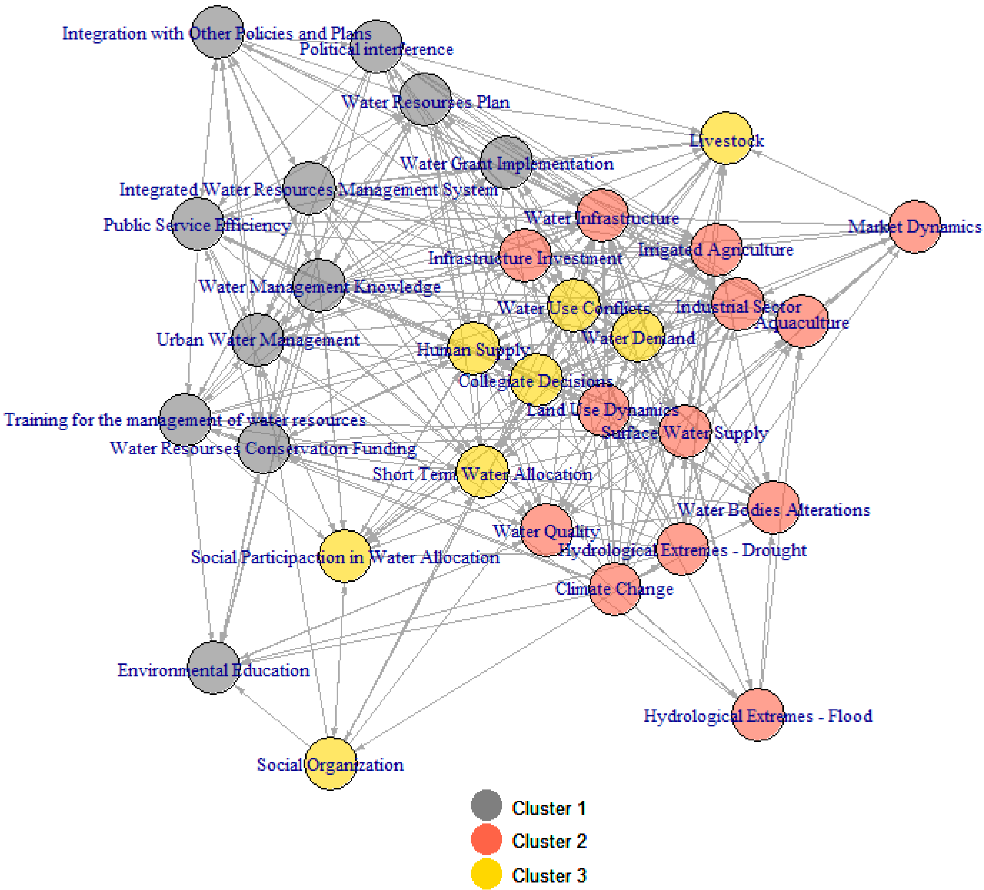
3.3.2.8 Cluster

The cluster is a set of points that are judged to be similar considering some characteristics. The levels of similarity are relative and there are more points similar and others less. In this way, there are many computational tools that help us to group the subgroups, but it should not be forgotten that sociological interpretation is essential (SCOTT, 2017).

The clusters must be formed from the central point of the graph, but it is not always possible to do it, especially in graphs with many points. Therefore, software R used an algorithm based on the greedy optimization of the quantity known as modularity, which counts the clicks so that they are grouped into subgroups.

Hence, the software divided the System under study in a quantitative way, according to the present connections between the points. In this way, three subgroups, subsystems or clusters were obtained as shown in Figure 15.

Figure 15 - Quantitative Cluster



Source: Author.

3.3.3 *Identification of Subsystems*

Observing the common characteristics of the points and from the researchers' knowledge about the water resources system under study, the qualitative analysis was made, and it was observed that it was possible to group variables into five subsystems, or clusters, according to Figure 16. The identified subsystems can be called “Economics and water use”; “Climate and hydrological regime”; “Politics, institutions and social dynamics”; “Quantity and Quality”; and “Internal dynamics of the hydrosystem”.

It can be observed that the input variables (blue) are located in the subsystem "Climate and hydrological regime" and "Politics, Institutions and Social Dynamics", which govern the behavior of the whole system. These directly impact the "internal dynamics of the hydrosystem", subsystem in which the two variables with the largest connections are located, that is, it is the integrating subsystem.

The subsystem called "Climate and hydrological regime" has four variables, three of which are "Climate Change", "Hydrological Extremes - Drought" and "Hydrological Extremes - Flood". These three variables are indispensable for the operation of the System, because they determine how much water it will have. The subgroup connects to all others, but mainly to the "Internal dynamics of the hydrosystem" and "Economics and Water Use", because climatic events directly impact the economy and arise conflicts over multiple uses of water. "Hydrological Extremes - Drought" and "Climate Change" have the largest connections, being 20 and 18 degrees consecutively, however "Hydrological Extremes - Flood" has the lowest of the entire system, 8.

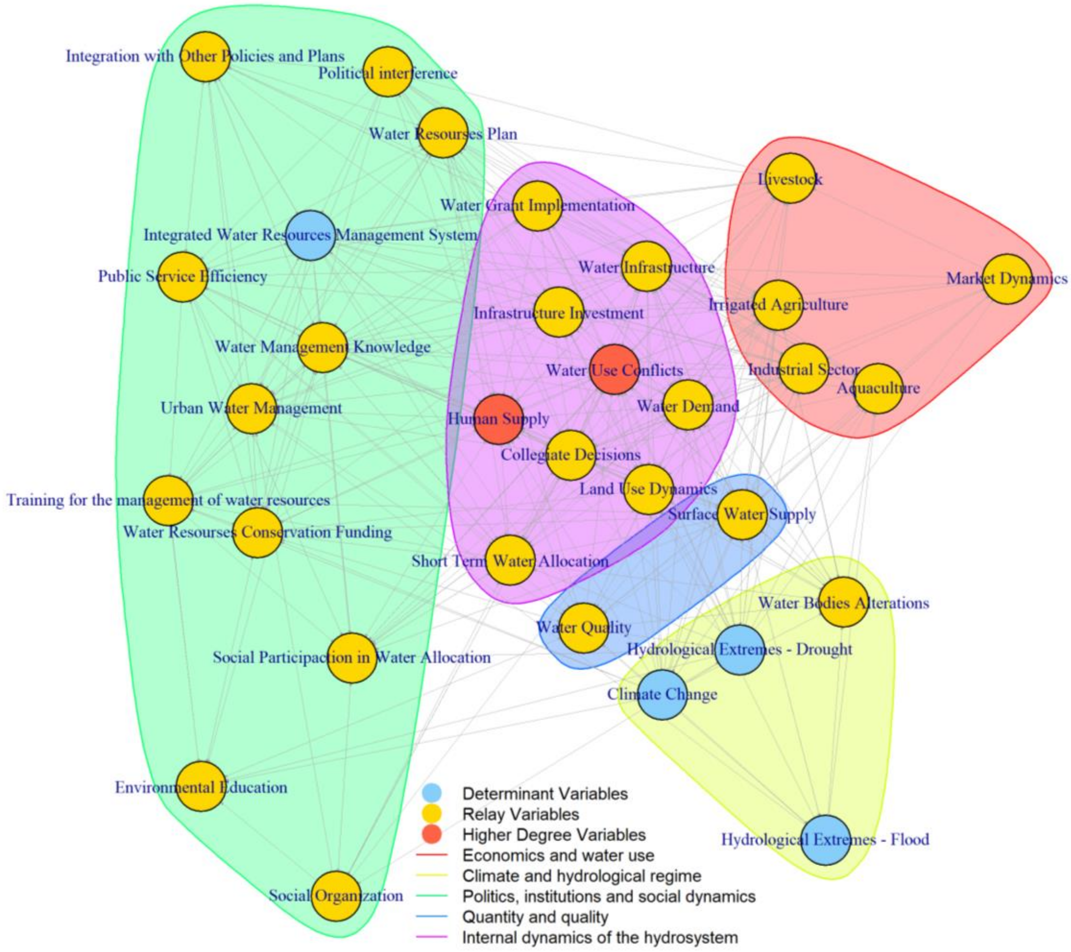
The smaller subsystem is called "Quantity and Quality", and it has only two variables: "Water Quality" and "Surface Water Supply". Although it is a small subgroup it relates to all groups. The first one has the largest number of connections with the group "Politics, Institutions and Social Dynamics", which is understandable, since it is linked to the fact that it does not pollute water and the population's awareness, as well as sanitary sewage and water supply which impact on the cost of supply. The second is a variable that has links to all members of the subgroups "Climate and hydrological regime" and "Economics and Water Use", because the variable depends on the first and is essential for the second. "Water Quality" has eigenvector centrality close to 0.5, and the vvalue obtained for "Surface Water Supply" is 0.63, which makes this variable more notable in the subgroup. In the same way as for degree, the second variable has more connections, totaling 30, against 22 of the first. "Surface Water Supply" comprises the largest value betweenness centrality of the System, 90.96, being very important for the network, as this value quantifies the number of times a node acts as a bridge along the shortest path between two other nodes.

The subsystem "Economics and water use" consists of variables related to the various types of water use that directly affect the market dynamics. They are interconnected with each other and with all subgroups, especially with "Internal dynamics of the hydrosystem". The most relevant variable for the system is "Irrigated agriculture" because it has more connections, it is a relevant activity in the state of Ceará. As for betweenness centrality, that and "Industrial Sector" have the highest value, 30.86 and 46.80, respectively. As for eigenvector centrality all variables have near-average values, except for "Market Dynamics", that stands at 0.33.

The next subgroup is considered the heart of the System, it was called "Internal dynamics of the hydrosystem". This is where the variables considered more central such as "Water use Conflicts" and "Human Supply" are located, they have the highest number of system connections and values of eigenvector centrality and betweenness centrality. "Water Demand" also has a high value of eigenvector centrality, 0.94, that is, it is a vertex with influence in the network.

The largest subgroup "Politics, institutions and social dynamics" consists of twelve variables and deals with the development of water policy, bodies, social participation, environmental education and the financing process of the system. Within this subgroup is located a key variable, "Integrated Water Resources Management System". This subsystem is linked to all others, but only three variables are linked to the group "Economics and water use": "Water Management Knowledge", "Water Resources Plan" and "Political Interference". The item with the highest number of connections, 32, is "Water Management Knowledge", and the lowest, 9, "Social Organization". The values of eigenvector centrality are smaller in this group, but "Social Participation in Water Allocation" stands out with 0.61, meaning that this node has importance for the subgroup. As for the centrality betweenness, "Water Management Knowledge" has the highest value of the subgroup, 58.36.

Figure 16 - Qualitative Cluster



Source: Author.

This system is considered dynamic, since each node, representing an actor, receives an assignment of values or responsibilities that can be modified according to political, socioeconomic, and climatic changes. This modifies the spread of information and the decisions that should be made. So relatively small changes in connectivity, can result in large changes in the whole network structure. This is called small-world networks. Also, these action processes are called actor-based models. They will be explored in further studies.

3.4 Conclusion

The analysis performed in this study through the application of Social Network Analysis is a way of reflecting on the behaviour of the water system, investigating its structural properties and identifying the subsystems that were created from the structural matrix.

Statistical measures in the SNA provided insights about the structure of the network. We measured reciprocity, transitivity, centrality (degree, betweenness, closeness, eigenvector) in the social network to identify the importance of vertices in the network. We observed that almost half of their connections are mutual and that it has a 60% probability of forming clusters. The degree distributions are a little homogeneous, the highest is 35 – "Water Use Conflicts", which is understandable as it is the main problem; and the lowest is 8 - Hydrological events - Flood, which is not so considerable since drought events are more recurring. Thus, using eigenvector centrality, we identify that there are certain vertices as the central in the social network, which are "Water Use Conflicts" and "Human Supply". For density, the graph was considered sparse, that is, the number of connections is not so close to the maximum number of edges. The results suggested that individuals and agencies / organizations have different roles in social networks during emergency responses.

The variables identified as well connected are "Water Use Conflicts", "Water Management Knowledge" and "Water Infrastructure", which is understandable since droughts have historically marked Ceará and climate change has been the subject of several discussions at the global level. Managing river basins is a difficult and not always possible task.

The division of the subgroups was analyzed in a quantitative and qualitative way, where from the disaggregation made through R, it was possible to observe the behavior of the System and to regroup it into five subsystems. Therefore, in the qualitative analysis it was observed that 37.5% of the variables are in the subgroup of "Politics, institutions and social dynamics"; 28,12% "Internal dynamics of the hydrosystem"; 15.62% "Economics and water use"; 12.5% "Climate and hydrological regime" and 6.25% "Quantity and Quality".

The model provides a promising approach by showing its ability to model and simulate the network structure, the interrelationships of variables, and the division of the subsystems of relevance to the Water Resources Planning, thus helping the decision making based on the critical variables of the system and those that can be modified. The analysis of networks proved to be useful in this sense, since it was possible to observe the interactions between its components in subgroups in a map, called graph, where it is of simple understanding through the nodes.

4. FUTURE WORK: NEW METHODOLOGY FOR BAYESIAN INFERENCE TO PROSPECTIVE CENARISATION IN WATER SAFETY PLANNING

4.1 Introduction

The planning of water resources in Brazil is quite complex, as there is a high uncertainty due to climatic and political-economic factors that impact the supply and demand of water. This study includes the search for water conservation, conflict resolution, vulnerability reduction, control and monitoring of pollution, among others. To ensure the competence of water resources management and to offer effective solutions, it is necessary that the planning consider the integration between the several factors that composes the water systems. Given this context, prospective winding up presents itself as an essential tool to aggregate the components of different spheres of water resource planning.

Scenarization has become recognized as a useful tool to deal with all the variables related to uncertainties and to generate solutions for the contemporaneous problems of water resources (Tarboton, 1995; Zacharias *et al.*, 2005; Pallottino *et al.*, 2005).

According to Marcial & Grumbach (2008), the prospective scenarios are combinations of variables that describe several possible futures and their links with the present. In addition, these studies are one of the most qualified instruments to delineate strategies in situations of uncertainty and risk, although it is not proposed to eliminate the uncertainties, only to reduce them (SOUSA, 2013; BRANDALISE *et al.*, 2012). Risks involving the environment and the water resources are in evidence, as the permanent availability of water is not certain, and the assessment of water risk is a challenge for all. According to the World Economic Forum - WEF (2015), the water crisis associated with scarcity and lack of access to potable water will be the greatest risk that humanity will face in the next decade. The elaboration of future scenarios is capable of assisting the management of water resources by exposing possible outcomes according to the current situation of the analyzed systems. Hence, it is necessary to make an analysis of such systems, to encompass all spheres of water resources planning.

The traditional approach to system analysis has become a mathematical and computational process being criticized by several researchers such as Rogers & Fiering (1986) for being limited in social, political, and environmental representation (HAROU *et al.*, 2009) to be used to understand the water resources systems that are composed of elements coming from two distinct and inseparable environments: the physical, chemical and biological environment and the cultural environment with social, political, economic and technological dimensions (WHITE *et al.*, 1992).

Therefore, it is necessary to investigate the variables from water resources system that influence the future scenario in order to provide technical and scientific support to decision makers in the management of water resources.

At the moment, there is no consensus or equation regarding prospective scenarization. It is proposed, therefore, the development of a methodology for the implementation of prospective scenarios based on Systems Analysis using Bayesian Inference and Social Networks Analysis, in order to provide guidelines for the management of water resources and, hence, support the National Water Resources Plan.

4.1.1 Inicial Question

By providing the possible outcomes of the future analyzed system, the scenarization can help to guarantee water security. However, it is possible to observe that technological, natural, social and behavioral factors influence each of the two topics, forming a system of great complexity with several variables and causal factors that are related. It is noteworthy that many works related to water systems face inaccurate data, increasing uncertainty and randomness.

Therefore, it is questioned whether it is possible to identify the components (social and natural) and their most relevant interrelations given a water resources system based on their specific characteristics. Is it possible to evaluate the possibility of occurrence (feasibility) given a supply, demand and institutional scenario of water resources in an uncertain future using a Bayesian approach?

4.1.2 Justification

Adapting to changing supply and demand patterns in water supply becomes an increasingly complex challenge. Modifications in the social, economic, political and institutional dynamics of society can interfere in the demand for water, as well as changes in the physical environment, such as climate change, are directly related to the water supply problems. It is the responsibility of the water resources managers to ensure the adaptability of the system to a changing world, providing solutions to an uncertain future (ANA, 2016).

The analysis of future scenarios within water resources planning provides a better understanding of how and why an alternative future can develop and especially the necessary steps that decision makers must follow in order to adapt to that future (MAHMOUD *et al.*, 2011). Thus, compreending the water resources systems is to understand a double complexity: the environment and the system itself. And to understand that systems to survive the complexity of the environment, which constantly creates new possibilities in unexpectedly forms, needs to evolve and change their structures (KICH *et al.*, 2010).

In order to analyze the nuances of a water resources system, considering the methodological weaknesses of the systems analysis, it is necessary a methodology that is able to recognize the diverse social, natural and physical components of a water system, as well as their interactions. However, in an investigation among the main journals within the theme of water resources studies, it was verified the absence of an integrated and robust methodology that allows the identification of the components and its interactions, thus to allow the analysis of the complexity of the diverse socioeconomic, cultural, physical and biological that takes into account the impact of the uncertainties of this changing world on the studied system.

The work is justified, therefore, by exploring and uniting new areas of scientific knowledge that will be able to assist the management of water resources by providing scientific basis to decision makers.

4.1.3 Main Objective

Develop and evaluate a prospective scenario methodology for Water Resources Planning (focusing on Basin Plans and Water Safety Plans) considering the various natural, infrastructure, institutional and socioeconomic components pertinent to water resources systems in order to consider the complexity and uncertainty of the system using Bayesian Inference and Graph Theory.

4.1.4 Specific Objectives

- Propose and develop a prospective scenario methodology that will allow the quantification of uncertainties and the integration of natural, social and infrastructure components in a river basin;
- Develop methodology using Social Network Analysis (graphs) that allows the identification of the components (natural, social, physical infrastructure) of a hydrosystem identifying their interrelationships and relevance;
- Model these networks using hierarchical Bayesian networks techniques to assess uncertainties and identify the possibility of occurrence of the analyzed scenarios;
- Develop modeling that quantifies water supply and demand in the proposed scenarios;
- Analyze the risks in water supply by modeling the allocation of water in the constructed scenarios.

4.2 Bibliographic Reference

In this section, concepts related to the themes considered important for the development of the work will be presented, which are: System Analysis, Prospective Scenarios, Bayesian Networks and System Network Analysis (graphs). The lattest will be addressed in the methodology.

4.2.1 Systems Analysis

Systems analysis emerges from the General Theory of Systems developed by a German biologist Ludwig von Bertalanffy as a structural-functional approach according to which the function of the system is constituted in what must be done for its structure remains the same (KICH *et al.*, 2010).

The application of systems analysis to water resources planning began more intensely in 1956 at the Havard Water Program of the Graduate School of Public Administration. This project aimed to optimize water resources systems through mathematical models and time series analysis

(MAASS *et al.,* 1962; GRIGG, 1996). Systems analysis allows the systematic examination of a vast number of different alternatives to achieve a goal. In the strictly physical view, systems are sets of elements united by a relation of interdependence. Such a relationship can be used to test a given element and check whether or not it belongs to the system (HERMANN, 1971).

4.2.2 Prospective Scenarios

Scenarization thecniques began to be used after World War II as a strategic tool to predict the possible consequences of a nuclear war. Since then, scenarios have been used in various planning fields and in the decision-making process with the purpose of exploring future uncertainties in a coherent, consistent and plausible way (KAHN, 1962; YOE, 2004; DONG, 2013).

Prospective scenarios initiate from the present and open a cone of possible futures. They are the most important step of strategic planning due to the guidelines for decision-making that they provide.

There are two outstanding experiences of prospective studies applied to the water resources area: World Water Council (2000) and United Nations Environment Program (UNEP) 2003 (UNEP, 2004). Both studies aimed to achieve strategies for the development of sustainable actions for water resources, thus prospective scenarios were elaborated. These works were internationally relevant because they mobilized several people to elaborate prospective scenarios. (NASCIMENTO *et al.*, 2010).

Abdoli *et al.* (2017) used the strategic prospective associated with the Micmac method (Matrix Multiplication applied to a classification), developed by Michel Godet in 1994, that allows to identify the components of the system and its key variables, that is, the variables that influence the whole system which should be the main target of the prospective studies through a structural analysis (GODET, 2000). This was done in order to outline a development plan for the province of Bushehr, Iran, which is an area of extreme importance for the oil and gas industry. The study identified 30 factors of great importance and later created four scenarios on a horizon until 2025.

Surahman *et al.* (2018) used strategic prospective and scenario building to identify the most influential and dependent variables in an Indonesian agricultural production system to allow the short-term agricultural use of degraded peatlands in a relatively sustainable way.

4.2.3 Bayesian Networks

The term inference or induction is a process that requires the knowledge of a part to draw conclusions about the whole. Bayes' theorem was introduced by the mathematician and reverend Thomas Bayes in the 18th century. However, it was only in the twentieth century that its importance as a statistical tool became recognized. It was considered a counterpoint to Classical Statistics (BECKMAN, 1980).

Bayesian networks are tools used to deal with uncertainties, complexity, and causal relationships. They present the probabilistic causal relationship between a set of random variables, their conditional dependencies and provide a joint conditional probability distribution (HORNÝ, 2014).

They are presented as a combination of graphs and probabilities, consisting of a Directed Acyclic Graph (DAG) composed of nodes {X1, X2, ..., Xn} and links, where nodes represent the random variables of the model, and the connections are the causal relationships between the variables, and a Joint Probability Distribution (JPD) associated with the graph. The model can then be represented by the notation B <G, φ>, where G represents the graph and the nodes, and φ, the JPD (HORNÝ, 2014; ZHANG *et al.*, 2014).

A conditional probability distribution is assigned for each variable (node). The DAG structure will form the joint probability distribution, which is factorized from the series of conditional probability distributions. This process is generalized in Equation 10, where π (Xi) is the antecedent variable of Xi and P (Xi | π (Xi)) is the conditional probability distribution of Xi. Once the DAG structure is established, the calibration of the model is done by incorporating the input variables with their due conditional probability values (CASTELLETTI; SONCINI-SESSA, 2007; HORNÝ, 2014).

$$P(X_1, \dots, X_n) = \prod_{X_i \in (X_1, \dots, X_n)} P(X_i | \pi(X_i)) \quad (10)$$

Bayesian inference can occur both bottom-up, where the evidence is known and the most likely cause is inferred, as well as top-down, where the probability of an effect will be calculated once the probable causes are known.

Studies with application of Bayesian decision theory in hydrology began in the 70's, being developed until the present day. The different areas of application include the analysis of the uncertainty in the frequency of flood occurrences, groundwater analysis and hydrogeological monitoring networks, among others (DAVIS *et al.*, 1972; GORSSER; GOODMAN, 1985; MCPHEE; YEH, 2006). The use of Bayesian networks was applied in participatory management of water resources (CASTELLETTI, SONCINI-SESSA, 2007, ZORRILLA *et al.*, 2009, VAROUCHAKIS, PALOGOS and KARATEZAS, 2016), opening further the range of applications of this network tool.

Bayesian inference is a widely used method, although it has not been applied to prospective scenarization, becoming an innovative study. The Bayesian inference and the Social Network Analisys methods are being used in other areas of science and it is possible to observe the innovation of the scenarios approach applied to the water resources system from these tools.

4.3 Methodology

4.3.1 Application Area: Jaguaribe-Metropolitan System

The models developed in this project will be applied in the Jaguaribe-Metropolitan system, located in the central-northeast region of the State of Ceará which is responsible for supplying the Metropolitan Region of Fortaleza. Figure 15 spatially illustrates the area to be studied, presenting the reservoirs and water transfer channels.

The two basins are integrated by two channels of water transfer in the region under study, they are: the Eixão das Águas and the Canal do Trabalhador. The process of water transfer is marked by local and interregional conflicts, which means a dispute in the development of the territory, thus the process of water allocation is gaining visibility. There are still the physical and operational restrictions of the system that must be considered for the region's water security.

Figure 17 - Application Area

Source: Author.

The state of Ceará is located in the northeastern region of Brazil. According to Ordinance No. 05, dated October 10, 2002, Ceará has 148,826 Km² of territory, of which 86.82% of this total is characterized as semi-arid, according to the update of the geographical and social map of the Brazilian semi-arid, carried out through of the Ordinance of March 16, 2005, of the Ministry of National Integration, which gave a new delimitation to the semi-arid region. According to the IBGE 2010 census, this state has a population of more than 8 million inhabitants and has high evaporation and great spatial variability of the rainfall regime.

4.3.2 Materials

The data will be obtained in numerical and linguistic forms, through information made available on electronic sites or acquired in physical form with competent agencies and / or professionals, based on the application of questionnaires, interviews and focus groups.

This information will be socioeconomic and climatological, among them it is possible to mention population dynamics, GPD, irrigated area, industrial demand, climate change models published by the IPCC, and other variables that will arise according to the needs of the study.

The modeling will be developed with the use of free software R which is an important tool in data manipulation, where it's possible to create your own analysis functions, and GeNIe software, which is decision-making software based on theoretical principles dynamic Bayesian networks and influence diagrams developed by BayesFusion LLC.

4.3.3 Method

The integrated analysis presents, essentially, six steps and three main items: Social Network Analysis, Bayesian Inference application and network simulation to obtain scenarios.

4.3.3.1 Step 1: Obtain System Data

For the development of the study, a bibliographic research was initially carried out to collect variables that characterize the water resources system of the state of Ceará. This list was obtained from the study entitle Prospecção no Universo das Águas of Nascimento *et al.* (2010) and it is composed of 47 variables described in Annex A. During the development of the research, these variables will be re-evaluated through interviews with specialists in the area.

These variables will be used in the elaboration of a structural matrix, known as the Micmac method developed by Michel Godet in 1994 (GODET, 1994). Micmac allows the identification of the components from the system and its key variables, that is, the variables that influence the whole system and that should be the main target of the prospective studies.

For each pair of variables will be answered on the existence or not of direct relation using the following indicators:

(0) has no influence;

(1) weak influence;

(2) average influence;

(3) strong influence;

It will be evaluated which is the most influential and dependent variable of the system. The influence will be given by the sum of the indices in the same line of the square matrix. While the dependency will be represented by the sum of the indices in the same column.

Subsequently, an investigation will be made to assign values to the variables. This work will include research on electronic websites and / or interviews with professionals from relevant bodies, such as the Secretariat of Water Resources (SRH) and the Water Resources Management Company (COGERH), members of the basin committees, including users, public and civil society. Also the Delphi Method, which consists of a forecasting technique will be applied through systematic collection of opinion from a structured group of experts (OLIVEIRA *et al.*, 2008). As a form of consultation will be used questionnaires and interviews.

4.3.3.2 Step 2: Social Network Analysis (graphs) using the free software R.

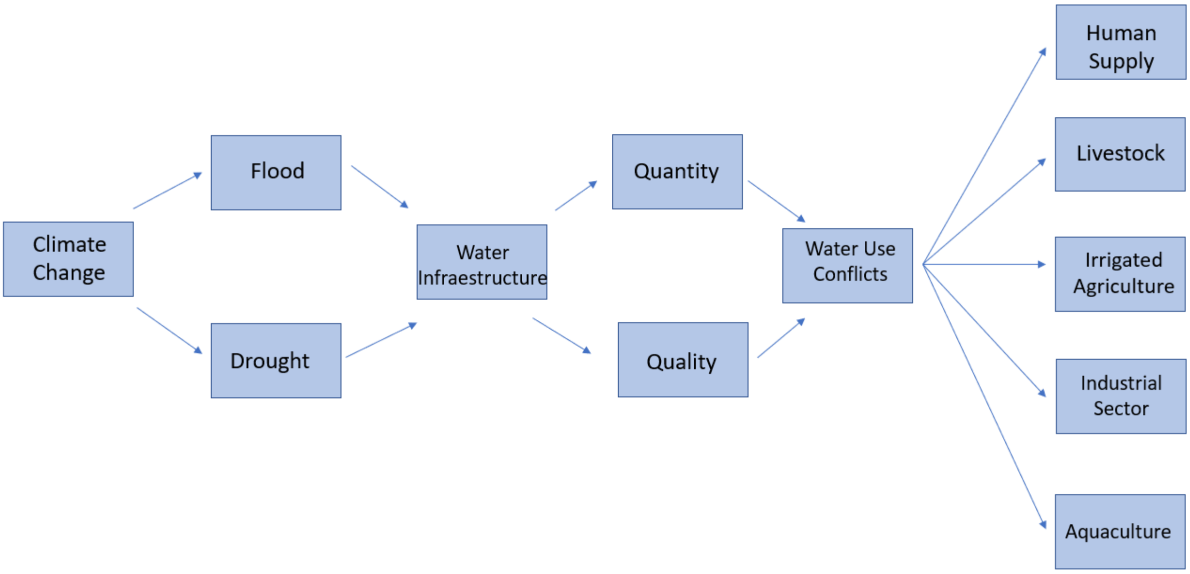
The Figure 4 represents the graph of interrelationships of variables, which was developed using the socioeconomic and natural variables introduced in Annex A. The graph is distributed as follows: the variables with less dependence are located in the extremities, while those with high dependence are interconnected in the center. Thus, the interrelations between its elements are determined, and it is possible to identify the structure and interrelations of the socio-natural system for the analysis of the Metropolitan Jaguaribe system. The key variables of the system were: Critical hydrological events (Drought and Flood), Climate change and Institutional Implementation of SINGERH.

Then, it is intended to extend this analysis involving Social Network Analysis in order to find a general equation for any system using the free software R.

4.3.3.3 Step 3: Application of Bayesian inference in free software R

The Figure 16 illustrates the DAG that was pre-defined by analyzing the relationships between the variables through the graph of Figure 4, which presents a scheme of variables considered key to the scenario building. A probability will be assigned to each node. From Equation 11, it is obtained the JPD, that is, the total probability. This chart can change on account of its links to the development of the study and the reassessment of the variables. The result can still receive more variables and factors, making it more complex and robust.

Figure 18 - Directed Acyclic Graph (DAG)



Source: Author.

Each box of the DAG is a node v and represents a random variable Zv. Together, they form the following set V:

$$V = \left\{ \begin{matrix} \text{Climate Change, Flood, Drought, Water Infraestructure,} \\ \text{Quality, } Quality\text{, Water Use Conflicts, Human Supply,} \\ \text{Livestock, Irrigated Agriculture, } Industrial \text{ Sector,} \\ Aquaculture \end{matrix} \right\}$$

$$V = \{\mathrm{c}, \mathrm{f}, \mathrm{d}, \mathrm{wi}, qt, ql, \mathrm{wc}, \mathrm{hs}, \mathrm{l}, \mathrm{ia}, \mathrm{is}, aq\} \tag{11}$$

The vector Zv = (Zm, Zc, Zs, Zi, Zqt, Zql, Zcm, Zah, Zap, Zai, Zat, Zaq) is assumed and JPD PZv (zv) is desired for the DAG. Applying the variables of Equation (11) in Equation (10), the factorized CPD representing the above DAG is given by Equation (12):

$$
\begin{aligned}
&P_{Z_V}(z_V) \\
&= P_{Z_c}(z_c) P_{Z_{f|c}}(z_{f|c}) P_{Z_{d|c}}(z_{d|c})\, P_{Z_{wi|d,f}}(z_{wi|d,f}) P_{Z_{qt|wi}}(z_{qt|wi}) P_{Z_{ql|wi}}(z_{ql|wi}) P_{Z_{wc|ql,qt}}(z_{wc|ql,qt}) \\
&P_{Z_{hs|wc}}(z_{hs|wc}) P_{Z_{l|wc}}(z_{l|wc}) P_{Z_{ia|wc}}(z_{ia|wc}) P_{Z_{is|wc}}(z_{is|wc}) P_{Z_{aq|wc}}(z_{aq|wc}) \qquad (12)
\end{aligned}
$$

The filled values will influence the water infrastructure and consequently the other items. So, the program must analyze these impacts.

4.3.3.4 Step 4: Network's simulation using R and GeNIe softwares

After obtaining the values, the network will be analyzed from a routine developed in software R and GeNIe. The performance of the models will be validated from consultation with specialists. This consultation will be done through interviews and focus groups with professionals from members of the basin committees.

4.3.3.5 Step 5: Quantification of demand and water supply

For the most probable system configurations obtained in the Bayesian network will be made an estimate of the demand and the water supply for the elaboration of future scenarios for the Jaguaribe-Metropolitan System. According to Nascimento *et al.* (2010), in the choice of scenarios the extremes must be selected, that is, one with greater probability and one with smaller, since it is intended to cover the largest space of plausible futures. Thus, for each future configuration of the system, the demand and water supply will be quantified.

For the quantification of urban demand, the projection of the population will be carried out initially through the logistic curve method, estimating, then, the per capita consumption. The demand for irrigation will be estimated from the quantification of the consumption per hectare according to the different types of crops present in the analyzed basin, considering the present data in the basin plans (MAYS, 1996).

For industrial demand, the technical coefficients elaborated by the Ministry of the Environment (2011) will be used, considering the demand of each industrial class according to its production.

4.3.3.6 Step 6: Water Safety Analysis

Considering the results obtained during the water balance, it is followed the diagnosis of it by the simulation of the system developed using the Aquanet tool, similar to the methodology applied by Cid (2017). It will be possible to analyze the most viable scenarios and the Water Safety of the Jaguaribe-Metropolitan System, which appears as an alternative for performance analysis, assisting Water Resources Planning and Basin Plans and Water Safety Plans.

4.4 Expected Results

The results provided by the computational program will consist of a scenario methodology in which, by implementing the variables with quantitative data, the analysis of one or more future scenarios will be obtained with the purpose of assisting the decision making starting from the critical variables of the system and those that can be modified.

It is expected that the process of Bayesian Inference and Social Network Analysis will provide the necessary subsidies for the qualitative and quantitative analysis of the scenarization and that they can robust methodologies to be applied in different water systems. It is also expected that the results can serve as a conceptual and technical basis for managers' decision making regarding the prioritization of resources and policies in order to alleviate the impacts of drought felt by the population of Ceará.

The project will offer as technical and academic contribution:

• Prospective scenarization of the Jaguaribe-Metropolitan System;

• Scenarization methodology applicable to water systems;

• Critical and technical assessment of Water Safety intrinsic to Water Systems;

• Decision support system for the management of water resources.

5 CONCLUSIONS

It was verified the importance of applying a strategic vision to the management of water resources, indicating a series of advantages arising from a foresight attitude regarding conflicts over water use. Thus, MicMac and SNA made it possible to identify the system variables as well as their interactions and the behavior of the system.

After analyzing the most influential and dependents variables of the system, it was possible to find the key variables, that is, the variables necessary for the system to function, they are: Critical hydrological events (Drought), Climate change, and Institutional Implementation of SINGERH. This reinforces the drought situation in which the State of Ceará is located.

The SNA allowed us to study the network, thus obtaining the metrics of the system. As well as identified that there are certain vertices that are central in the social network, which are "Water Use Conflicts" and "Human Supply". They have a direct impact on the economy.

After the quantitative analysis, three clusters or subgroups were obtained according to the researchers' knowledge. It was possible to carry out a new analysis, called qualitative analysis, where five subsystems were identified: "Economics and water use"; "Climate and hydrological regime"; "Politics, institutions and social dynamics"; "Quantity and Quality"; and "Internal dynamics of the hydrosystem". Each one plays its role in the functioning of the model studied.

The development of this study faced difficulties due to the logistics of applying the matrix, because it was very difficult to persuade researchers to predict them, as it became exhausting. Also, the logistics of applying the matrix was complicated, since the financial resources were scarce.

It is recommended that in future work, as explained in the last chapter, the development of a new methodology that associates prospective scenarios methodology with Bayesian Inference that can be applied to any Water Resources System. In this methodology should be given quantitatives values to the variables and ought to be performed based on the key and central variables identified in this present analysis in order to provide guidelines for the management of water resources, to assist decision making and, consequently, to support the National Water Resources Plan. This methodology allows to delineate future actions and measures.

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ANNEX A – LIST OF SYSTEM VARIABLES

Water Quality	Pollution Control Infrastructure	Livestock	Political interference
Surface Water Supply	Human Supply	GDP	Environmental Education
Underground Water Supply	Social inequality	Infrastructure Investment	Integrated Water Resources Management System
Water Bodies Alterations	Social Organization	Water Use Efficiency	Water Resources Conservation Funding
Hydrological Extremes – Drought	Information access and transparency	Urban Water Management	Training for the management of water resources
Hydrological Extremes – Flood	Populational Dynamics	Waterbodies Classification	Water Use Conflicts
Intentional Bioinvasion	Water Demand	Water Resources Plan	Market Dynamics
Accidental Bioinvasion	Irrigated Agriculture	Short Term Water Allocation	Public Service Efficiency
Biomes Conservation	Industrial Sector	Social Participation in Water Allocation	Water Management Knowledge
Land Use Dynamics	Fishing	Water Grant Implementation	Integration with Other Policies and Plans
Estuaries Systems	Aquaculture	Climate Change	Water Infrastructure
Mortality due to waterborne diseases	Tourism and Leisure	Collegiate Decisions	

Source: Author.

ANNEX B – POTENTIAL STRUCTURAL ANALYSIS MATRIX

Variables	COD	1	2	3	4	5	6	7	8	9	10	11	12
Water Quality	1		0	0	0	0	0	1	2	3	2	3	3
Surface Water Supply	2	3		2	3	3	3	1	1	3	2	2	2
Underground Water Supply	3	2	2		1	0	0	0	0	2	2	1	1
Water Bodies Alterations	4	3	3	3		1	1	1	2	3	3	3	1
Hydrological Extremes - Drought	5	3	3	3	2		0	0	0	3	3	2	2
Hydrological Extremes - Flood	6	3	3	3	3	0		0	3	2	3	3	2
Intentional Bioinvasion	7	3	0	0	0	0	0		0	3	1	2	1
Accidental Bioinvasion	8	3	0	0	0	0	0	0		3	1	2	1
Biomes Conservation	9	3	3	2	3	1	1	0	0		2	3	2
Land Use Dynamics	10	3	3	3	3	1	2	2	2	3		3	2
Estuaries Systems	11	1	1	0	0	0	0	0	0	2	1		1
Mortality due to waterborne diseases	12	1	0	0	0	0	0	0	0	1	1	0	

Source: Author