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ARTICLE

Blockchain technology and complex flow systems as opportunities for water governance innovation[1]

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ABSTRACT

According to the World Economic Forum, the water crisis ranks among the five most dangerous risks to global welfare. In this context, water governance is becoming increasingly vital in various regions, especially as the multiple and competitive uses of water mount increasing pressures on its supply. Despite the evolution of water governance rationales, global water resources are, unfortunately deteriorating. Current water governance models are limited by two intertwined aspects: financial sources and trust. In this context, the objective of this paper is to discuss how blockchain technology can aid in improving water governance, increasing

1 This work is a result of the project "*Abordagem simultânea e inter-relacionada das dimensões de sustentabilidade para a melhoria da gestão de recursos hídricos: o caso da bacia do Rio Jundiaí*", 2016-2021, support by *Programa de Apoio à Pós-graduação e à Pesquisa Científica e Tecnológica em Desenvolvimento Socioeconômico no Brasil* (PGPSE), *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (Capes), notice n. 42/2014.

financial transparency, and stakeholders' trust. Such an improvement could be achieved, for example, with the creation of cryptocurrencies to encourage actions aimed at the conservation of water resources, and also via the adoption of smart contracts.

KEYWORDS | Blockchain Technology; Management of River Basins; Cryptocurrencies; Smart Contracts

Inovação na governança da água: o papel da tecnologia *blockchain* e dos sistemas complexos de fluxos

RESUMO

A crise hídrica está entre os cinco principais riscos globais apontados pelo Fórum Econômico Mundial. A governança é importante porque os múltiplos e competitivos usos da água se acentuam, colocando pressões adicionais sobre a sua oferta em várias regiões. Apesar da evolução na governança da água, infelizmente se observa globalmente uma deterioração dos recursos hídricos. Dentre as principais limitações da governança da água estão o aspecto financeiro e a confiança. Nesse contexto, o objetivo do presente trabalho é discutir como a tecnologia *blockchain* pode auxiliar na melhoria da governança da água, tais como no aumento da transparência, no financiamento e na confiança. Esse aprimoramento poderia ser alcançado, por exemplo, com a criação de criptomoedas para incentivar a adoção de ações voltadas para conservação dos recursos hídricos e adoção de *smart contracts*.

PALAVRAS-CHAVE | Tecnologia *Blockchain*; Gestão de Bacias Hidrográficas; Criptomoedas; Contratos Inteligentes

1. Introduction

The importance of governance in ensuring the availability and quality of water for present and future generations has been widely accepted by society and is actively discussed by various institutions and researchers. (BICUDO; TUNDISI; SCHEUENSTUHL, 2017; OCDE, 2015; PAHL-WOSTL, 2015; UN ENVIRONMENT, 2018; WORLD RESOURCES INSTITUTE, 2017). According to Tundisi (2013), water governance is one of the critical factors in regional and socioeconomic development and is poised to become a strategic problem as the 21st century progresses. In this sense, various regions are seeing the multiple and competitive uses of water mount increasing pressures on its availability and quality (AALST et al., 2014; FREIRE-GONZÁLEZ; DECKER; HALL, 2017; WORLD RESOURCES INSTITUTE, 2017; WWAP, 2015).

Due to the increasing complexity of the problems caused by these social and economic pressures, water governance models have been going through several adaptations (CAMPOS, 2007; LANNA, 2001; OCDE, 2015). According to Tundisi (2013), for most of the twentieth-century water governance was centralized and sectorized, guided mainly by the concern for public supply and quality, to meet the demands of public consumption, fishing, and navigation. More recently, the governance process has changed its focus to river basin management, incorporating actions to allow for multiple water uses in an integrated and non-sectorized manner. Water governance has also become predictive, aiming to anticipate processes and phenomena. The Brazilian case reflects this trajectory. The 1934 Water Code (BRASIL, 1934) strictly heeded the economical use of water. The National Water Act of 1997, on the other hand, moved forward to identify the river basin as a management unit, while recognizing the multiple uses of water (BRASIL, 1997).

Despite the evolution of water governance, global water resources are, unfortunately deteriorating (PAHL-WOSTL, 2015). In the World Water Forum, held in 2000, the Global Water Partnership's Framework for Action declared that the water crisis was mainly a crisis of management (i.e., governance) (TUNDISI, 2013; WORLD WATER COUNCIL, 2000). This assertion is echoed by the WWAP (2006),[2] according to which the water crisis has little to do with a lack of technology, its causes stemming from governance-related shortcomings. The "OECD Principles on Water Governance" document (OCDE, 2015) presents ample

2 World Water Assessment Program – WWAP, by Unesco.

evidence of significant governance failures. Such failures hamper the formulation and implementation of water management policies. To overcome them requires a set of responses and good practices. According to OCDE (2015), no single solution fits the myriad of water governance challenges. Instead, models must be tailored to regional particularities, recognizing that governance is highly context-dependent, and that water policies need to adjust to different realities. In other words, the present consensus is that management is contextual, that public policies have to adapt to various water resources and territories, and that governance models have to adapt to ever-changing circumstances (OCDE, 2015).

The water crisis is one of the top five global risks identified by the World Economic Forum (WEF, 2018). This finding reflects, among other factors, that water management actions have come short of safeguarding the provision and quality of water resources (BICUDO; TUNDISI; SCHEUENSTUHL, 2017; HIPEL et al., 2015; NEWTON, 2016; PAHL-WOSTL, 2015; ZIOLKOWSKA; PETERSON, 2017).

One of the main limitations of current water governance models lies in their funding sources (CURLEY, 2016). They still rely heavily on enterprises that have been contributing to environmental degradation (LIETAER et al., 2012). According to Paiva Sobrinho and Córdoba-Brenes (2017), the introduction of the current international monetary system, known as the dollar standard (DUNCAN, 2011; LUND et al., 2013; PAIVA SOBRINHO; ROMEIRO, 2016a), has produced a significant expansion of global credit, causing increased economic pressures on ecosystems and compromising their conservation status. Also, the sharp expansion of credit has led to the acceleration and aggravation of global economic and financial crises (DUNCAN, 2011; MILNE, 2009; PAIVA SOBRINHO; ROMEIRO, 2016b). In this dire scenario, it is imperative for innovation to take place in water governance's theoretical and practical framework, especially in regards to two points: increasing the financial resilience of systems that aim to solve water problems at various spatiotemporal scales; and increasing the participation of civil society[3] in actions for resolving rural or urban water problems. The crux of our argument is that water governance's theoretical framework should incorporate knowledge derived from the sustainability of complex flow systems (ULANOWICZ et al., 2009). In practical and operational terms, it should employ blockchain technology for the creation of

3 According to the European Union, civil society "is a collective term for all types of social action, by individuals or groups, that do not emanate from the state and are not run by it" (EUROPEAN UNION, 2019). For a theoretical discussion on the concept of civil society, see Avritzer (2012).

new governance structures, based on smart contracts and water governance-oriented cryptocurrencies (PAIVA SOBRINHO et al., 2017a).

Thus, the objective of this paper is to discuss how blockchain technology can aid in improving water governance, increasing financial transparency, and trust. Such an improvement could be achieved, for instance, with the creation of cryptocurrencies and the adoption of smart contracts to foster actions aimed at the conservation of water resources (PAIVA SOBRINHO et al., 2017b). Traditional financing methods make governance systems more susceptible to economic and financial crises – as in the Brazilian fiscal crisis, which had a significant impact on environmental policies (WWF, 2017).

This article has four sections, besides Introduction and Conclusions. The second one presents blockchain technology, different consensus mechanisms, and smart contracts. Next, we discuss the theoretical aspects of water governance. The fourth section offers information on the sustainability of complex flow systems. In the last, we discuss how water governance can be improved by incorporating knowledge on the sustainability of complex flow systems and blockchain technology.

2.2 Blockchain technology

Nakamoto (2008) created the blockchain technology together with the first and most famous and well-known application is Bitcoin.[4] Narayanan et al. (2016) define blockchain technology simply as a chain of blocks connected by hash functions. Hash functions are mathematical functions that are easily calculated from an input value. Conversely, however, it is almost impossible for the input value to be derived from the one output by the function. This feature of the hash function endows the blockchain with a property of immutability: in other words, once the data is stored in blocks, these blocks are made immutable by the hash function and thenceforth cannot be changed. Any attempt to tamper with the stored data will be noticed since such an effort would alter the values output by the hash function.

It is worth noting that the blockchain is stored in multiple devices, such as servers and personal computers. Thus, every device belonging to the cryptocurrency's peer-to-peer (P2P) network can have a complete copy of all its records. These copies are synchronized, so every new record has to be validated by the system, according to specific consensus mechanisms (NARAYANAN et al., 2016). In this

4 <https://bitcoin.org/en/>.

sense, different consensus mechanisms can be said to represent different paths for the evolution of blockchain technology.

2.1 Proof-of-Work consensus mechanism

The first-generation blockchain came to fruition in 2009, with the code implementation of the ideas of Nakamoto (2008). This early iteration used a Proof-of-Work (PoW) algorithm as its consensus mechanism. PoW is computationally expensive because it requires nodes of the cryptocurrency's network – known as miners – to solve intensive mathematical puzzles, and then offer the solution as a proof-of-work used to validate new data for insertion into the blockchain. As a reward for their efforts, miners receive freshly minted Bitcoins.

In the beginning, anyone could mine Bitcoin (i.e., solving these mathematical puzzles) using an ordinary laptop. Today this is no longer possible. Due to the expansion of the Bitcoin network and the considerable computational effort required – an effort that increases periodically as the difficulty rises – mining is now restricted to companies able to purchase and maintain computer farms with significant processing capacity. These entail high investments and maintenance costs, that is, large amounts of capital.[5] These massive investments could lead to the restriction of access to new Bitcoins to a few significant players, negating Bitcoin's decentralized nature. To avoid this risk, new consensus mechanisms have emerged, such as Proof-of-Stake (PoS) and Delegated Proof-of-Stake (DPoS).

2.2 Proof-of-Stake consensus mechanism

To overcome the limitations of the Proof-of-Work consensus mechanism, Peercoin developers created the Proof-of-Stake (PoS)[6] mechanism, announced in 2012. The coin adopts a hybrid approach, combining PoW and PoS. The first cryptocurrency employing the PoS mechanism was NXT.[7]

In the PoS mechanism, the participant of the system can certify transactions and insert them into the blockchain without possessing significant hardware capabilities. One only has to own cryptocurrencies. Moreover, the chance of an account being chosen as the creator of a new block depends on the number of cryptocurrencies

5 Currently, mining pools also exist.

6 <https://peercoin.net/>.

7 <https://nxtplatform.org/>.

owned by this account. Generally speaking, PoS also implies that all cryptocurrencies are created at launch, although the total amount can remain constant or increase over time. Given the above, the basic version of the PoS mechanism also differs from Bitcoin by offering no block rewards. Validators are rewarded with transaction fees.

Larimer (2014) states that "while NXT and Peercoin have each solved the problem of who should generate the next block, they have not sufficiently solved the problem of making the blockchain irreversibly secure on time." Peercoin's version of the mechanism requires at least six blocks (1 hour), while NXT's one needs a minimum of 10 blocks.

2.3 Delegated Proof-of-Stake consensus mechanism

Delegated Proof-of-Stake (DPoS) is a consensus algorithm that allows stakeholders and system users to have control over who is responsible for certifying the transactions that will be inserted into the blockchain. This mechanism was introduced in 2013 by the team responsible for the Bitshares blockchain platform. In DPoS, even small-time cryptocurrency holders can delegate their transaction certification prerogatives. In other words, agents in this kind of network have a voice regardless of the number of cryptocurrencies they own and can use it to transfer their certification rights to another agent (with better capabilities).

The difference between a regular PoS system and a DPoS system is akin to the difference between direct democracy and representative democracy. In the PoS system, every cryptocurrency portfolio can be a part of the transaction validation process, forming the distributed consensus and receiving cryptocurrencies in return. In the DPoS system, every cryptocurrency portfolio is empowered to vote for delegates, and these delegates are the ones who perform the function of validating transactions and maintaining the blockchain while being rewarded with transaction fees (LISK ACADEMY, 2019).

Thanks to the DPoS consensus mechanism, BitShares can manage roughly 50,000 transactions per second (tps), while ensuring block integrity and security.[8] The evolution of the BitShares blockchain is the EOSIO, released in June 2018.[9] EOSIO development is still in early stages, so parallel computing is yet to be introduced. However, its transaction rate can already exceed 3,000 tps. After incorporating parallel processing and other computational features, the EOSIO blockchain should be able

8 Further details can be obtained at the BitShares (https://goo.gl/m5JGJm).

9 <https://eos.io>.

to operate at more than 500,000 tps. It will also be able to execute smart contracts without the operating costs of other blockchain platforms, such as Ethereum.[10]

2.4 Smart contracts

Smart contracts are self-contained sets of digital instructions, computer programs, which operate within a blockchain. Nick Szabo coined the term in 1994.[11] Szabo (1994) defines smart contract as:

> *[…] a computerized transaction protocol that executes terms of a contract. The general objectives of smart contract design are to satisfy common contractual conditions (such as payment terms, liens, confidentiality, and even enforcement), minimize exceptions both malicious and accidental, and minimize the need for trusted intermediaries. Related economic goals include lowering fraud loss, arbitrations and enforcement costs, and other transaction costs. (*

The term smart contract came about before the introduction of blockchain technology but gained more relevance with the appearance of the Ethereum blockchain in 2014. Ethereum allows these contracts to be executed once they have been allocated adequately within the blockchain. As the first blockchain platform to support smart contracts, as in the case of Bitcoin, its limitations are already overcome by alternatives such as EOS. The first of these limitations, which we have previously discussed, lies in Ethereum's limited transactions per second (tps) capabilities. A second limitation is related to transaction costs, which are significantly higher in comparison to those of the EOSIO platform.

Regardless of the particularities of different blockchain platforms, smart contracts have standard features, such as the use of oracles. Oracles are reliable sources of information and data that serve as inputs for smart contracts. For example, the temperature measurement service of a government institution could use an oracle to provide temperature data, which would then be utilized in a smart contract representing a bet between two people. In this example, the smart contract would work as follows: if on a specific day, at a given time, the temperature equals a specific value, one of the gamblers loses the bet, while the smart contract automatically transfers an asset (cryptocurrencies) to the winning party.

10 <https://ethereum.org>.

11 <http://www.virtualschool.edu/mon/Economics/SmartContracts.html>.

Smart contracts can also help organized civil society to come up with new institutions, which could issue their own cryptocurrencies and establish rules of self-regulatory administration. Thus, smart contracts could enable the management of water resources in a decentralized manner, with less exposure to the pitfalls of the economic system (DUNCAN, 2011; MILNE, 2009; PAIVA SOBRINHO; ROMEIRO, 2016a). This rationale is directly related to the development of Decentralized Autonomous Organizations (DAOs). The operating rules for a DAO can be defined in smart contracts stored in a blockchain platform. The use of a public blockchain platform would make these rules openly accessible.

It is worth noting that all forms of blockchain technology, regardless of consensus mechanism, allow people who do not trust each other to collaborate without relying on a central authority or centralized management. In this sense, blockchain technology is known as a trust-building "machine" (THE ECONOMIST, 2015). According to Mougayar and Buterin (2016), the blockchain makes intermediary financial agents – such as conventional banks – wholly obsolete. Avoiding intermediaries financial agents opens a path for the creation of parallel monetary systems, immune to the structural shortcomings of the current international monetary system (DUNCAN, 2011; PAIVA SOBRINHO; ROMEIRO, 2016a).

In any case, the use of blockchain technology to solve socio-ecological problems is already a reality. One example is SolarCoin, created to promote the use and generation of solar energy (SOLARCOIN, 2019). The SolarCoin foundation makes their cryptocurrency available to those able to prove that they have generated solar electricity. It states that 99% of SolarCoins will be transferred to solar producers over the next 40 years. Each SolarCoin in circulation represents 1 MWh of solar energy, generated by solar panels installed in residential and commercial establishments.

Paiva Sobrinho and Romeiro (2016b) propose a prototype cryptocurrency known as Oxys, aimed at promoting sustainable development. The coin would foster actions targeting issues such as greenhouse gas emissions and the recovery and conservation of green areas. As the name suggests, Oxys' rationale is inspired by oxygen's life-giving role in nature. Oxys would be generated when an agent performs verifiable actions aimed at solving socio-ecological problems at any spatial scale—local, regional, national, or international. Verberne (2018), for instance, proposes the use of blockchain technology for tracking maritime fish populations. Other, novel applications will gradually emerge, especially in water governance.

3. Principles of water governance

Several research contributions are defining the concept of water governance (BICUDO; TUNDISI; SCHEUENSTUHL, 2017; PAHL-WOSTL, 2015). Interestingly, some of these contributions highlight popular participation as an essential component (EMPINOTTI; JACOBI; FRACALANZA, 2016). The document "OECD Principles on Water Governance" (OCDE, 2015) merits special consideration, although it suffers from several theoretical limitations, which we will point out here.

The OCDE (2015) has established general principles to help countries develop their water governance models. It has also contributed to the development of transparent and result-oriented public policies. The organization's water governance principles are based on three complementary and mutually reinforcing dimensions:

- effectiveness: [to define] clear sustainable water policy goals and targets at different levels of government, to implement those policy goals, and to meet expected objectives or targets;
- efficiency: [to maximize] the benefits of sustainable water management and welfare at the least cost to society;
- trust and engagement: [to build] public confidence and [ensure] inclusiveness of stakeholders through democratic legitimacy and fairness for society at large.

These principles and OCDE's contribution as a whole are of vital importance. Nevertheless, knowledge is in constant evolution and, in this sense, we argue that water governance should incorporate innovations stemming from the theory of sustainability of complex flow systems (ULANOWICZ et al., 2009). The approach conceptually and empirically demonstrates that, in these systems, sustainability relies on the combination of resilience and efficiency. The degree of magnitude of these components depends on two variables: structural diversity and connectivity. Socio-ecological systems, such as those related to water resources management, fall within the category of complex flow systems. Thus, their sustainability is a function of their resilience and efficiency (LIETAER et al., 2012; ULANOWICZ et al., 2009). Further details on the sustainability of complex flow systems are presented in section 4.

In addition to those indicated by OCDE (2015), other aspects of water governance would also have to undergo a process of innovation. Several authors agree that improved water governance should also incorporate anti-corruption practices, introducing greater transparency to water resources management, especially in regards to financial resources (EMPINOTTI; JACOBI; FRACALANZA, 2016; UNDP, 1997; UNESCO, 2003). In this sense, we are convinced that the application of blockchain technology to water governance can increase resource allocation transparency, providing security against data tampering practices, and growing trust among stakeholders. Adoption of this technology to solve water resources-related problems should increase as more people and institutions become aware of its potential. Precisely in this vein, Paiva Sobrinho et al. (2017b) outline a cryptocurrency system for the conservation of water resources in the Jundiaí River basin, in the state of São Paulo. The cryptocurrency's goal is to encourage the basin's inhabitants to carry out actions aiming at the conservation of water resources, both in rural and urban areas.

4. Sustainability of complex flow systems

A complex flow system is composed of several interconnected parts, through which the flow of water, energy, money, species, or products and services occurs (ULANOWICZ et al., 2009). In other words, it is a system naturally or artificially delineated to allow the transfer of objects between its parts. As previously explained, the sustainability of these systems depends on two properties (LIETAER et al., 2012; ULANOWICZ et al., 2009): resilience, and efficiency. The authors show that sustainability is greater when resilience surpasses efficiency. However, if too much resilience or efficiency is introduced, sustainability decreases. The region where the sustainability of the system is maximum is called the window of viability. Thus, the challenge is to design socio-ecological systems that lie precisely within this region.

The concept of resilience is related to the number of alternative pathways a system can rely on to remain functional, in case of a disruption of the system's main flow pathway. In the economic systems of several nations, for example, small and medium enterprises depend on a single type of credit: bank credit. These enterprises are subject to the negative consequences of economic crises, which create unfavorable bank credit conditions. In this case, resilience is zero because entrepreneurs have no alternative to bank credit.

Since 1934, entrepreneurs in Switzerland have the WIR at their disposal. The WIR currency differs from the Swiss franc, the dollar or the euro, which are created by central (FEDERAL RESERVE OF BOSTON, 1982), commercial banks whenever their customers get into debt (MCLEAY; RADIA; THOMAS, 2014; WERNER, 2016). The WIR is offered by the WIR Bank, whose governance depends on small and medium entrepreneurs, and not on the financial system. The WIR Bank issues credit through a mutual credit clearing system, that is, small and medium-sized businesses obtain a loan without incurring debt as they would in a traditional bank.12 Stodder (2009) argues that the WIR bank favors the development of small and medium-sized businesses, especially in times of economic and financial crisis (when traditional credit is more difficult to obtain). In this context, entrepreneurs can receive credit from the WIR bank using a mutual credit clearing system.

According to Lietaer et al. (2012), the current financial system is unsustainable due to its high efficiency and zero resilience. High efficiency implies that the components of a system have a greater connection to and dependence on a single source of resources. In the case of an economic system, this refers to the relationship and interdependence of economic sectors on the traditional banking system. The issue here is that banks generally do not provide credit for solving socio-ecological problems since this activity will rarely yield any financial returns. Additionally, banking system problems negatively impact other economic sectors, as the credit flow is interrupted or no more extended functions as before.[13] To ensure that the economic system remains operational even when one source of credit is compromised, different financial sources have to be created. Otherwise, even a state intervention will not be able to circumvent the situation completely.

In the case of the economic system, several authors (LIETAER et al., 2012; PAIVA SOBRINHO; ROMEIRO, 2015) point to the incorporation into the monetary system of new types of money, or complementary currencies,[14] outside the control of traditional financial institutions. One alternative type of money is comprised of cryptocurrencies developed based on blockchain technology.

Although water governance models have been through a significant evolution (OCDE, 2015; TUNDISI, 2013), they continue to have zero resilience due to relying on only one type of money as a financial source. This dependence is a severe fault in the governance of water resources, but could be solved with a combination of multiple actions, such as a) creating awareness of the existence of various types of money, such as cryptocurrencies (PAIVA SOBRINHO; CÓRDOBA-BRENES,

12 For more details on the operation of the mutual credit clearing system, see Paiva Sobrinho (2016).

13 Another example would be an automobile able to run on petrol, ethanol and natural gas. Such an automobile would be more resilient than one depending entirely on petrol. In case petrol supply problems start occurring, the former can rely on other sources of energy, maintaining its flow, while the latter cannot.

14 Lietaer (1999) defines complementary currency as an agreement within a community to accept a non-national currency as a medium of exchange. The complementary currency performs social functions for which the official currency was not intended.

2016; PAIVA SOBRINHO; ROMEIRO, 2016a); b) using blockchain technology to ensure transparency and trust.

One should also point out that several open source applications are being built on top of the EOSIO blockchain technology. One example is BeSpiral,[15] which is intended to aid people and institutions in learning, simulating, designing, and implementing[16] cryptocurrencies to foster actions aimed at solving socio-ecological problems, such as the conservation of watersheds. Cryptocurrencies created via the BeSpiral platform are a means of exchange and not a means of accumulation since their use is restricted to the communities that created them.

5. Advancing water governance

The incorporation of knowledge on the sustainability of complex flow systems (ULANOWICZ et al., 2009) and blockchain technology can significantly contribute to the improvement of water governance. The use of cryptocurrencies specifically created to encourage actions that contribute to the conservation of water resources can increase the socioeconomic resilience of the current water governance system. This use would make water governance less dependent on the current financial system, which is susceptible to recurrent crises. Besides, the technology could increase confidence in water basin management.

As previously noted, traditional water governance systems depend on a single type of currency (e.g., the Brazilian real). This governance model is unsustainable due to the risk of its activities being interrupted by economic crises. Such systems can be efficient, but they are not monetarily resilient. On the other hand, water governance systems financed by more than one type of money increase their chances of remaining functional even in the face of economic crises. Also though the WIR system is not geared towards water governance, it can be thought of as a reference. It points to the importance of resilience in socioeconomic systems aimed at solving socio-ecological problems—such as guaranteeing the supply of drinking water.

Initiatives in the use of cryptocurrencies to support water governance should gain new ground as professionals and society learn more about blockchain technology and the sustainability of complex flow systems. In Brazil, the Acqua cryptocurrency

15 This article's first author is a co-founder of the BeSpiral initiative. It is the first Brazilian Decentralized Application (DApp) created using EOSIO software (https://bespiral.com).

16 See the article "Criptomoeda é dinheiro?"

is a pioneering project being developed to support water governance in the Jundiaí River basin (PAIVA SOBRINHO et al., 2017b).

The incorporation of more than one type of money to an economic system can increase its socioeconomic resilience and, consequently, its sustainability. Increasing the monetary independence of water resource management systems using cryptocurrencies designed for that purpose is a necessary form of innovation. In that sense, Paiva Sobrinho and Romeiro (2017) argue that cryptocurrencies intended to aid in the conservation of threatened Brazilian biomes should include contributions from areas of knowledge such as social physics (PENTLAND, 2015) and system dynamics (STERMAN, 2002). Such recommendations may also be useful in the context of water governance-oriented cryptocurrencies. Operationally speaking, they are already being implemented on the BeSpiral digital platform.[17]

Blockchain technology can also significantly improve participation in water resources management. Campos and Fracalanza (2010) emphasize the importance of participatory mechanisms in water management, considered in terms of how this participation takes place. Examples of participatory aspects that merit analysis are: a) what part of civil society participates in river basin management processes; b) what participatory possibilities are available to social actors; c) what kind of participatory mechanisms can be created and how they can improve the level of awareness and intervention capabilities of new management actors; the role of conflict and consensus in the logic of water management.

To this date, community participation has done without blockchain technology. Smart contracts, however, enable water governance rules to be embedded in a blockchain platform, accessible for people to analyze and interact with. They can be created with the participation of concerned communities, and these communities can help establish what types of actions are encouraged, rewarding their agents with cryptocurrencies. Smart contracts can also enable the voting of topics of interest to occur without physical meetings (e.g., basin committee meetings), making full use of the security of blockchain technology.

Blockchain technology also enables water governance to occur in a distributed, non-bureaucratic way, with less dependence on the financial system and, consequently, less exposure to economic, fiscal, and financial crises. It also allows for increased transparency and oversight (e.g., audits), as well as the mitigation of illegal practices.

17 <https://bespiral.com/>.

6. Conclusion

The water issue has gained an important space in society at large, in the political agenda, and scientific and technological research. The World Economic Forum declared water insecurity as one of the top five global risks of the 21st century. To a degree, the problems stemming from the water crisis are associated with the shortcomings of existing governance models and their support instruments. Despite ongoing efforts to optimize such models, several areas could still be improved, such as: increasing the independence of governance systems from the socioeconomic system, specifically about sources of funding; increasing the degree of transparency and trust among stakeholders; stimulating the participation of civil society in a watershed and environmental management.

All evidence indicates that the theoretical and practical framework of water governance needs to be refined. In this sense, a window of opportunity is emerging with the development of blockchain technology, smart contracts, and the advances in the area of sustainability of complex flow systems. Blockchain technology equates to storing data in blocks, interconnected by cryptographic functions that prevent data tampering. The most popular application of this technology is the Bitcoin cryptocurrency. However, blockchain technology can also be used as a tool for solving several problems, such as river basin management.

Smart contracts are another interesting application. These are a set of digital instructions (protocols), contained within a computer program connected to the blockchain. Smart contracts can enable society to issue its own cryptocurrencies, tied to water resource management rules, for example. Platforms such as SolarCoin and BeSpiral are already doing this.

Finally, complex flow systems are composed of interconnected parts through which the flow of water, energy, money, species, or products and services occurs. The sustainability of these systems depends on their resilience and efficiency. Sustainability is created by an optimal combination of resilience and efficiency. The challenge is to design socio-ecological systems that operate according to this precise combination.

Applying these three innovations to solving socio-ecological problems can contribute to increases in water governance resilience, effectiveness, efficiency, trust, and commitment. These innovations could allow water governance to become less susceptible to the adverse effects of economic, financial and fiscal crises, as well as more transparent and less susceptible to corruption, besides stimulating greater participation of society in the management of water resources. At the present moment, an important step would be to encourage the dissemination of these innovations in society, highlighting their potential for solving complex socio-ecological problems.

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