Blockchain and IoT for Drinking Water: A Game-Changing Opportunity or a Risky Proposition

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Key messages

- The decentralized nature of blockchain combined with the data gathering potential of Internet of Things, IoT, can significantly aid drinking water management.
- These technologies can be successfully implemented for water management in areas with water scarcity if there is government support, public and private investment, and high local and international cooperation.
- Implementation of blockchain and IoT in drinking water management must have a foundation in inclusivity which focuses on knowledge surrounding utilization rather than the mechanics behind it.
- A focus on inclusivity will help reduce existing gaps between the Global North and the Global South in access to drinking water. However, it may contribute to exacerbating gaps in knowledge and thus create an interdependent relationship between developing and developed nations.
- Even with decentralized solutions like blockchain and IoT, there must be centralized governance to facilitate cooperation between all agents involved in drinking water management.

High-quality drinking water is becoming increasingly scarce due to climate change. This lack of water access results in marginalized people being unable to meet their basic human rights. Today, there are 1.42 billion people living in high or extremely high-water vulnerability areas[1]. Problems with water mismanagement on a local and national level in developing countries also worsen water vulnerability (see Annex A).

The United Nations Conference on Trade and Development (UNCTAD) Technology and Innovation Report 2021 identified 11 frontier technologies that have possibilities for sustainable development. Two of these technologies – blockchain and internet of things (IoT) – have been found to be utilized in some projects to tackle water mismanagement. Despite the promising potential, UNCTAD also acknowledged that there might be risks on further exacerbating the global North-South divide when implementing these technologies[2]. Therefore, this science policy brief aims to critically assess blockchain and IoT as a possible green window of opportunity for closing global economic, social, and digital divides between developing and developed countries by using these technologies as a new water management tool.

Blockchain and IoT Concepts

Blockchain is a digital ledger technology which allows for more transparent access to and trade in online data[3]. It works by storing data across many computers so that the record cannot be altered retroactively without the alteration of the original "blocks" of ordered records[4]. IoT is a wide and comprehensive network of various sensors and other devices, which feed information to one centralized data point[5]. Blockchain and IoT combined, create audit trails which enable transparent collecting and analyzing of data which cannot be modified and is stored in a decentralized manner[6].

Due to this decentralized nature of blockchain, there is no central data center needed for storage. Rather, information is shared among computers around the world, where it is put into the blocks which form the irreputable data chain which is blockchain[7]. This makes it suitable to be implemented in areas where there is no direct access to a data center. Furthermore, as there is no geographical confinement in using blockchain, areas which lack digital or electrical infrastructure, are hard to reach, or lack technical expertise, can still benefit from blockchain through its decrease in dependency on data centers [8].

Blockchain and IoT in Water Management

Blockchain technology can be used to create an efficient trust mechanism in water resource use processes. Precisely, the peer-to-peer "supply-use-consume-discard" process links created by blockchain can be an innovative and relevant utility for improvement of traditional storage and management of drinking water data[9]. It also makes it easier to issue and track water permits, as well as making obtaining permit information more secure and verifiable. The main difference between applications in water management and other applications of blockchain is how the data is generated. This is where IoT plays a role. IoT consist of several sensors and other smart devices which can monitor and report on, e.g., water levels, quality of water, and salt-water intrusion[10]. The IoT devices share the sensor data they collect, which is then sent to a collective cloud to be analyzed.

The characteristics of transparency, adaptability, accessibility, and its decentralized nature make blockchain suitable for water management in areas where water is mismanaged by a central authority and/or when local actors have no personal say in how their water is distributed, managed, or supplied[11]. The combination of blockchain and IoT-powered sensors for optimizing water data collection creates a reliable mechanism for tracking water quality, ensuring the accuracy and reliability of water quality information, identifying areas of poor water quality, clarifying people's responsibilities, and thus, in theory, ensure water security for residents[12] (see annex B).

This science policy brief will have a strong focus on how blockchain and IoT can be used as a tool to democratize access to water. The goal is to examine what utilization these technologies can bring and what externalities and assumptions to take into consideration during implementation, rather than providing a solution to geo-political conflicts which can arise from resource stress.

Threats and Opportunities of Implementation

To adequately examine whether IoT and blockchain can be considered a green window of opportunity for democratizing drinkable water access, there are certain environmental, political, and social risks which must be addressed. Social risks refer to the impact on communities where blockchain and IoT for water management would be implemented, whilst political risks are broader and refer to the governance of these communities. Because of Blockchain's total transparency, it can be a threat to the existing social and political order by reconfiguring the power dynamics in a community[13]. Furthermore, implementing Blockchain and IoT can exacerbate local inequities by increasing the gap between those who know how to work with these technologies and those who do not[14].

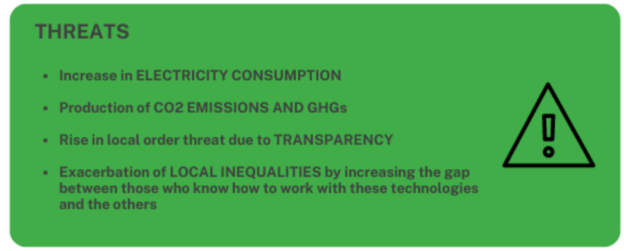


Figure 1. Threats of IoT and Blockchain Implementation

Moreover, an increase in the use of blockchain is expected to go hand in hand with an increase in electricity consumption, which in turn causes an increase in CO_2 emissions[15] [16] [17]. Furthermore, IoT devices use large amounts of electricity, contribute to landfills when discarded, and can directly release greenhouse gases (GHG) while operating[18] [19]. This puts to question the ability of these technologies to be considered green windows of opportunities.

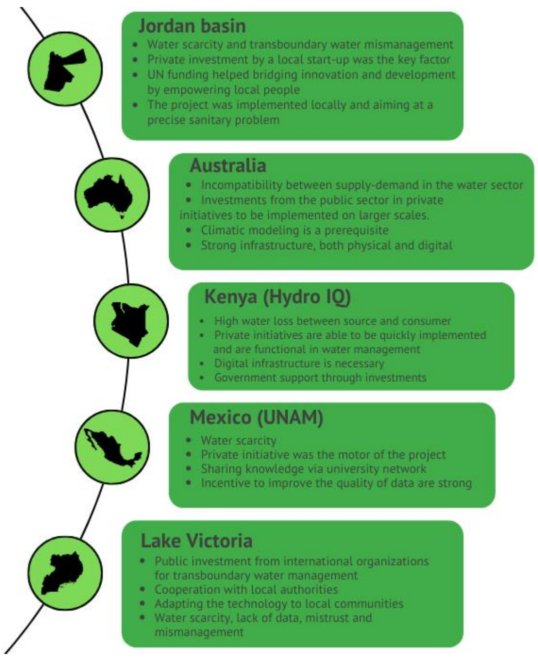
However, these technologies also have social and political opportunities that can counter-balance the effect of the risk based on individual preferences. The transparency can also be perceived as a benefit, increasing the trust among those who are impacted by a new way of water management and helping them adjust their water usage accordingly[20]. This adds to an increase in general welfare, with communities becoming more self-reliant and resilient with efficient water management[21].

Regarding environmental opportunities, there is an emerging energy-efficient alternative, namely green IoT. It is a specific type of IoT which reduces or even eradicates the GHG emissions caused by existing IoT applications[22] [23] [24]. In Annex C, the specifics of green IoT and its application to water management have been elaborated.

Figure 2. Opportunities of IoT and Blockchain Implementation

Case Studies

To critically assess this theoretical relevance of blockchain and IoT as a leverage for green and inclusive water management, it is essential to delve into field examples. Five different case studies were studied where these technologies presumably were tested for improvement of drinking water management. The five different regions (Fig 3) were chosen for the noted improvement that the technologies had in a specific phase of a water management project in the context of the increasing scarcity of the



resource (for further description of case studies, refer to Annex D). Water scarcity is a relative concept but can be identified as the inability of water supply to meet the long-term water demands of a population[25]. Based on this, main indicators of success or obstacles were drawn to analyze feasibility for further implementation across three developing regions as specified later (Libya, Viet Nam, and Darfur).

Figure 3. Five Successful Cases Chosen for Multicriteria Analysis

Multicriteria Analysis

Based on the case studies above and their different elements of success or failure, criteria have been established:

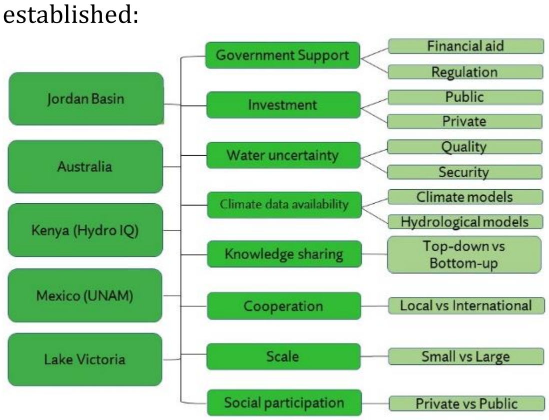


Figure 4. Criteria Analyzed from Five Chosen Cases

These criteria are a measure of success of the case studies mentioned before and are applied and analyzed to three distinct developing regions in three different areas of the world (Middle East, East Africa, and Southeast Asia) where there is protracted high-quality water scarcity and mismanagement, resulting in a certain degree of conflict surrounding water.

Libya

It can be concluded that blockchain and IoT for water management can be a viable solution to Libya's water uncertainty (see Annex F). Libya does not have any centralized authority due to a lack of strong government overseeing water usage, and its population has little awareness of the water they consume. The transparency and decentralized nature of blockchain can fit within the current decentralized system and can help overcome the knowledge gaps and lack of control the local population has over their own water consumption. Additionally, there are enough subsidies available to help reorganize the water management sector, and the digital infrastructure is expected to be up to par to facilitate a digital water management system.

Darfur

Taking these different criteria into account, we concluded that implementing blockchain for drinking water management in Darfur is not suitable (see Annex G). In Darfur, water is a commodity that is scarce due to migration of population due to conflict and climate change. Water is hoarded by elites, and it creates great disparity in water distribution. Blockchain and IoT represent an opportunity, which added to people's current cooperation, could provide data for equal water management. However, the problems which are persistent in the Darfur conflict surrounding water might not be directly linked to the access of information, but rather on the inaction to solve it. Furthermore, blockchain transparency could be a challenge in the communication between the different parties.

Viet Nam (Dong Nai River Basin)

The combination of an ever-growing climate stress and the impact of rapid development on quality of water and inequalities[26], makes the Dong Nai River a relevant area for implementation of innovative water management solutions and the technological optimization of sewer pipes and other wastewater treatment systems (see Annex H). Water quality assessment and hydrological predictions being concrete priorities for the government[27], new sensors and decentralized secured data appear as essential features to solidify the region's resilience to water stress. However, it is important to note that climate change related issues seem to lack grassroot awareness and an integrated network of local stakeholders. In the same perspective, lack of local climate change assessment and community knowledge[28] or involvement prevents visibility for social participation and inclusivity. Indeed, the implementation of such frontier technologies here could further impact the digital divide in the region.

Conclusions

The first scales, based on the five initial case studies, are the following:

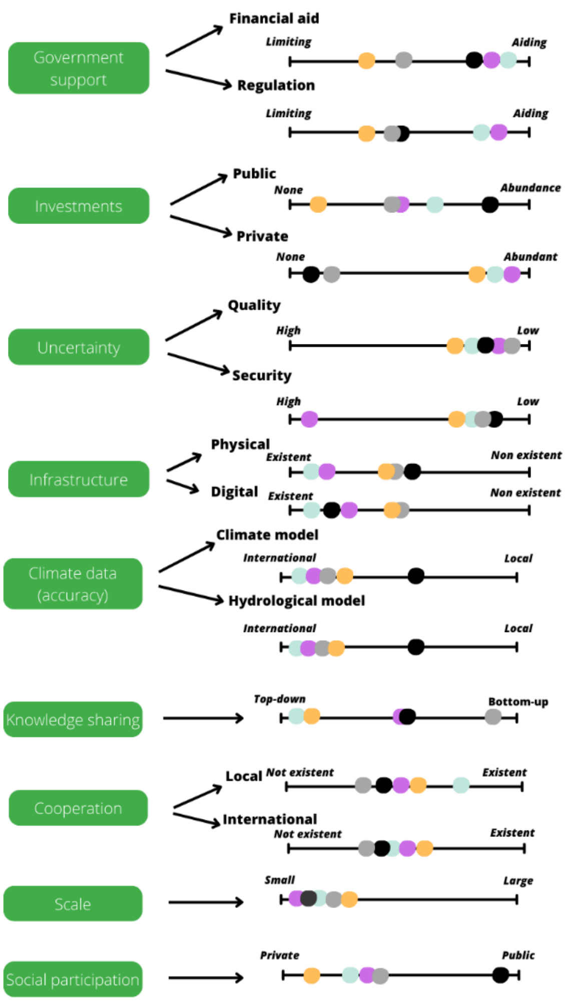


Figure 5. Multicriteria Analysis (yellow = Kenya; black = Mexico; purple = Australia; blue = Jordan Basin)

The following conclusions can be made:

- → Water uncertainty is the main incentive for implementation of blockchain and IoT in water management.
- → Private investments play a key role in supporting water management incentives, but this must be complimented by some degree of public support in the form of financial and regulatory help.
- → To be able to implement blockchain and IoT in water management, there must be physical and digital infrastructure which can support it. This infrastructure must be maintained and reliable.
- → Cooperation should always be there, but it is not necessary to have cooperation on intense levels at both international, national, local, community-based, etc., level.
- → Small scale is seen as a factor of success in the current implementations of blockchain and IoT in water management.

The other set of scales were based on the three applied case studies:

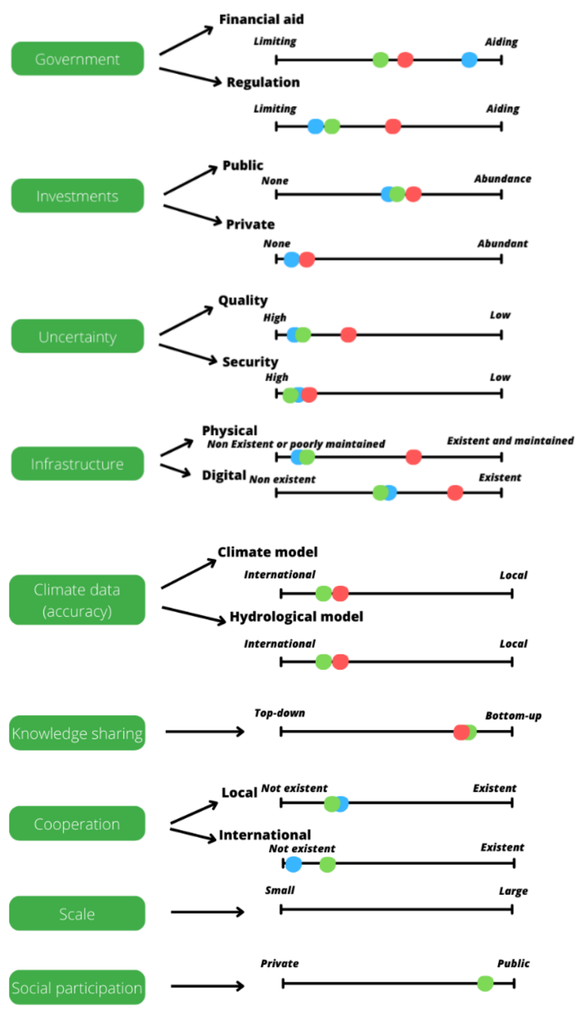


Figure 6. Multicriteria Analysis (blue = Libya; green = Darfur; red = Viet Nam)

From the case studies of Libya, Darfur, and Viet Nam, these conclusions can be made:

- → Even though there is support from public investments, private investments are lacking significantly.
- → There is high uncertainty of water which can be seen as a solid incentive for alternative water management systems using blockchain and IoT.
- → Infrastructure is lacking or not maintained in both the physical and digital domain, which can be considered a limiting factor in implementing blockchain and IoT water management.
- → There is little cooperation on all levels of society, which could be a limiting factor for implementation but does not directly mean it is impossible (based on the conclusions of previous case studies).

Several overarching key conclusions can therefore be made. Firstly, water uncertainty is a main incentive for implementation of blockchain and IoT in water management and should be present in all cases where blockchain and IoT are implemented. Secondly, private investments play a key role in supporting water management incentives, but there must be a degree of public support as well. Finally, cooperation between all levels of society is something which should be strived for, and which is expected to aid in successful implementation of blockchain and IoT in water management. The main conclusion which can be made however, is that for a decentralized technological solution like blockchain to be implemented, there has to be centralized governance to coordinate it.

Policy Recommendations

This brief shows that IoT in combination with blockchain has the potential as a water management tool to provide a powerful way to tackle chronic drinking water mismanagement. However, it is not a universal solution and policy must be adjusted accordingly to facilitate implementation. The following recommendations are directed at those who are involved in policy making on water management, at all levels of governance.

- → To implement blockchain and IoT for drinking water management, it is necessary **to organize discussion between private initiatives and institutions**. The private sector is well-suited for this task due to its ability to make decisions quickly and focus on innovation, as well as its capability of taking on a central governance role. To support these efforts, the **public sector should provide initial investment for small-scale private initiatives.** Small-scale implementation requires fewer upfront investments and infrastructure can be tailored to the specific needs and demands of a particular region or community.
- → **Implementors should create an inclusivity framework and combine infrastructure and technology with integration of local or indigenous heritage**[29][30], such as traditional climatic knowledge, valuing the “best of two worlds”. This can be done through formal and informal platforms such as **capacity-building**, **local workshops**, **citizens consultancy** and other **bottom-up** learning opportunities. This enables combining traditional knowledge with modern technology and infrastructure, so potential pitfalls of imposing foreign solutions on local communities can be avoided.
- → It is highly recommended to create an **educational tool for policy makers to understand the mechanisms and stakes of implementing blockchain and IoT in water management**. Indeed, as a complex frontier technology, policy makers are likely to encounter digital gaps and express caution or resentment towards blockchain implementation. It is also important as technology and infrastructure can have unintended consequences, particularly in remote areas where traditional social norms have a strong influence on people's behavior.
- → Lastly, **future policies should put importance on using green IoT instead of non-environmentally conscious IoT.** Green IoT has the potential to decrease power consumption and minimize e-waste. To make sure that the entire process is as climate neutral as possible, governments should aim to facilitate renewable energy to fuel blockchain and IoT in water management. Using the in this brief identified criteria as leverage, will ensure projects in water management using blockchain and IoT are sustainable and can be considered a green window of opportunity.

Annex A: Maps on water scarcity and water conflict

Water scarcity map of developing countries in the Global South[31]

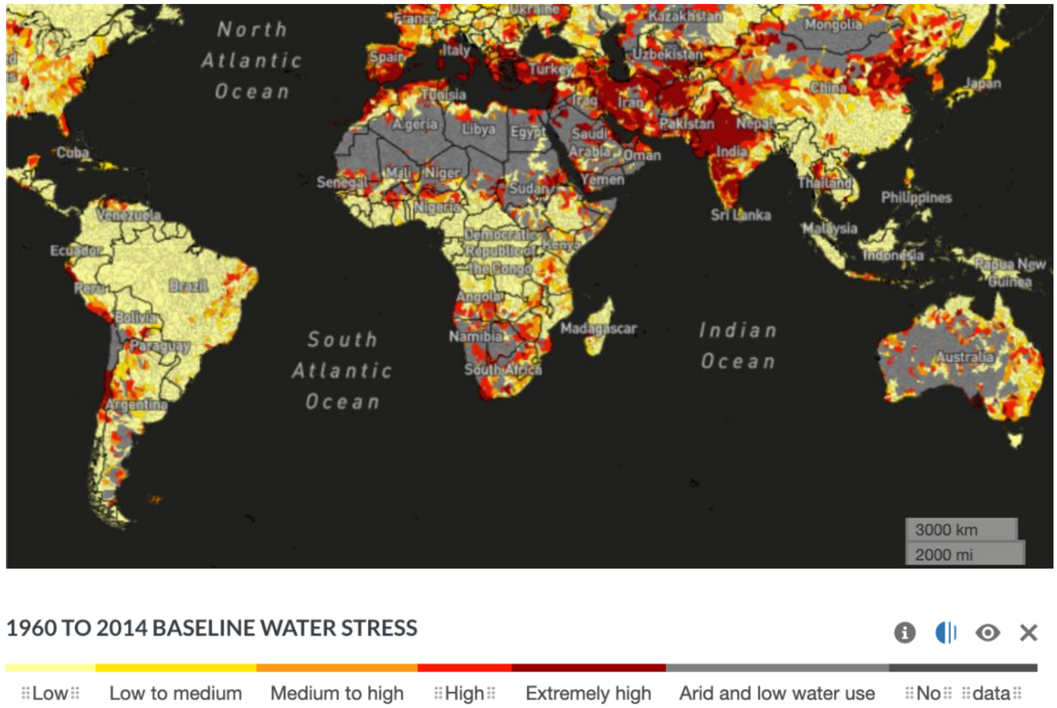


Figure 1: Baseline water stress: ratio of total withdrawals to available renewable water supplies. Higher values indicate more competition among users.

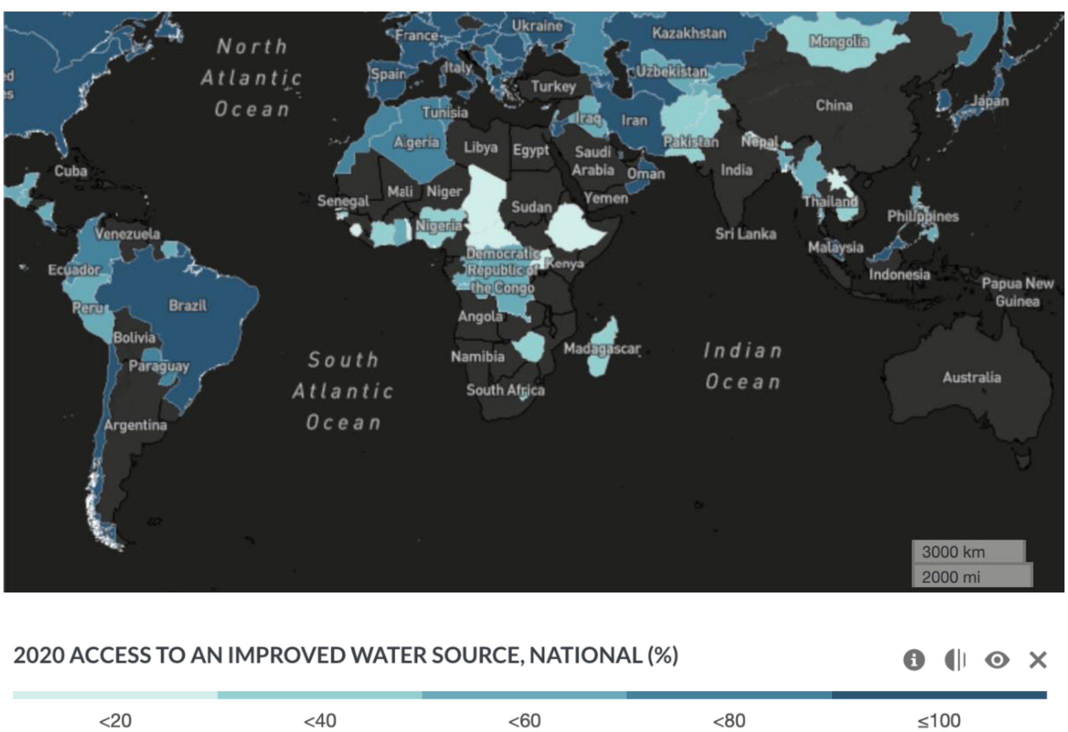


Figure 2: Access to drinking water: percentage of population with access to an improved drinking water source.

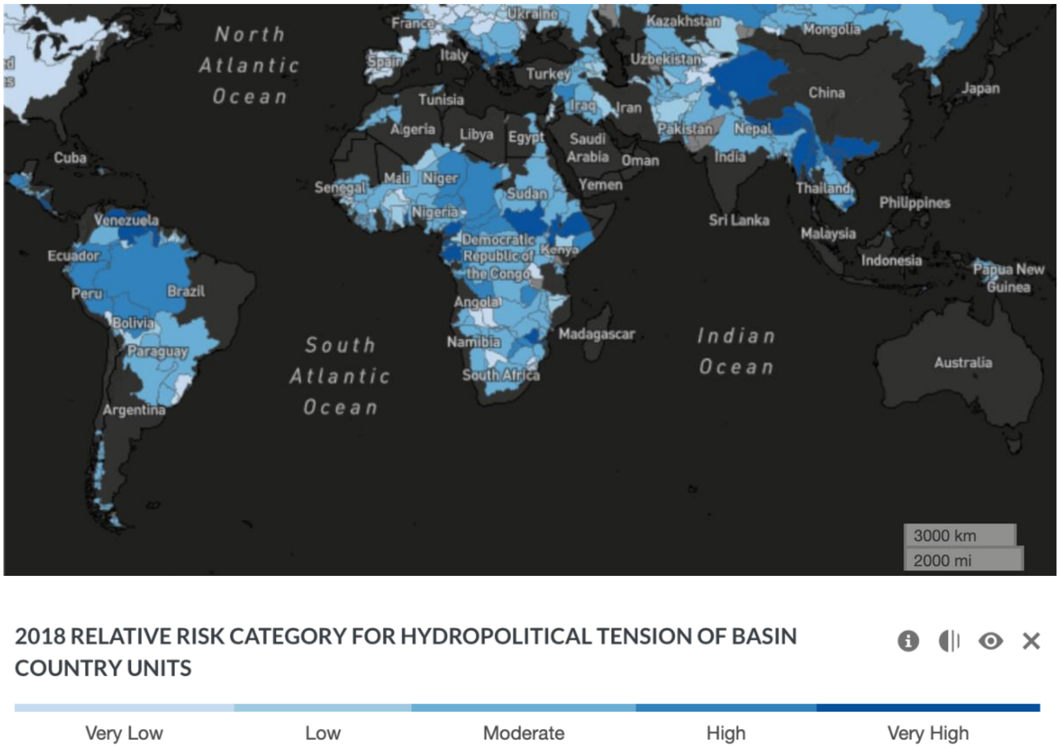


Figure 3: Hydro political tension for basin country units: relative risk of hydro political tension, based on the level of institutional vulnerability and level of hazard due to water infrastructure.

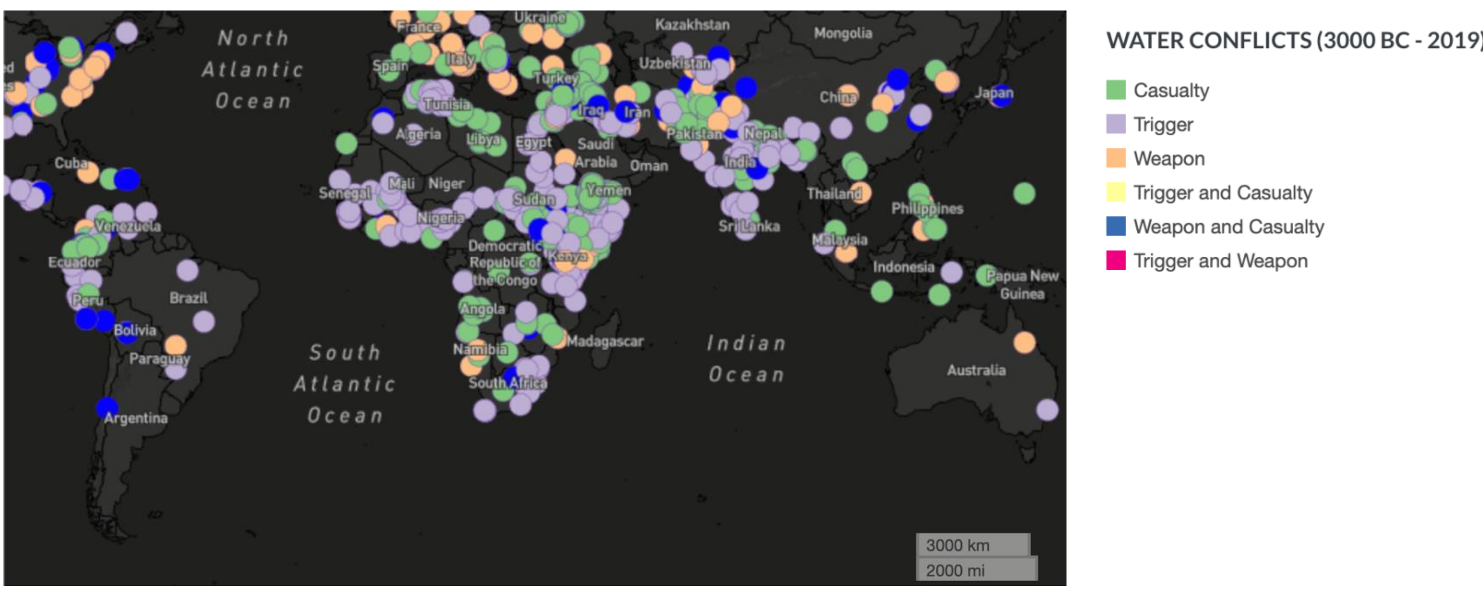


Figure 4: Water conflicts: locations where conflicts over water have occurred.

Annex B: Blockchain Concepts in Water Management

To fully grasp how Blockchain and IoT can be implemented in water management, solid understanding of how Blockchain functions is essential. Blockchain is a distributed ledger technology. Essentially this means that it stores data in the form of chains of data instead of the traditional solitary pieces of data which are stored in one centralized datacenter. When data enters a blockchain network, action is undertaken by data being transferred through the nodes. The network of nodes is a network which spans the entire globe and is distributed on individual computers of miners, those engaging in validating the transactions and receiving an award for their work.

Blockchain is widely known for its application in the financial-technology – fintech – industry. However, this way of data storage can also play a fundamental role in other sectors/ industry. In this paper, a link is made between blockchain and water management. The graph below is a visualization of how Blockchain can be implemented in water management divided into three different management modules. This science policy brief places a focus on water source, water supply, and water utilization management. As specified on the graph, smart contracts are an integral part in how blockchain can function within water management. Smart contracts are the pre-requisite blockchain having an applicational function. Smart contracts are defined as programs stored in blockchain that run when predetermined conditions are met, they are in essence the automated processed which run as a result of blockchain networks[32]

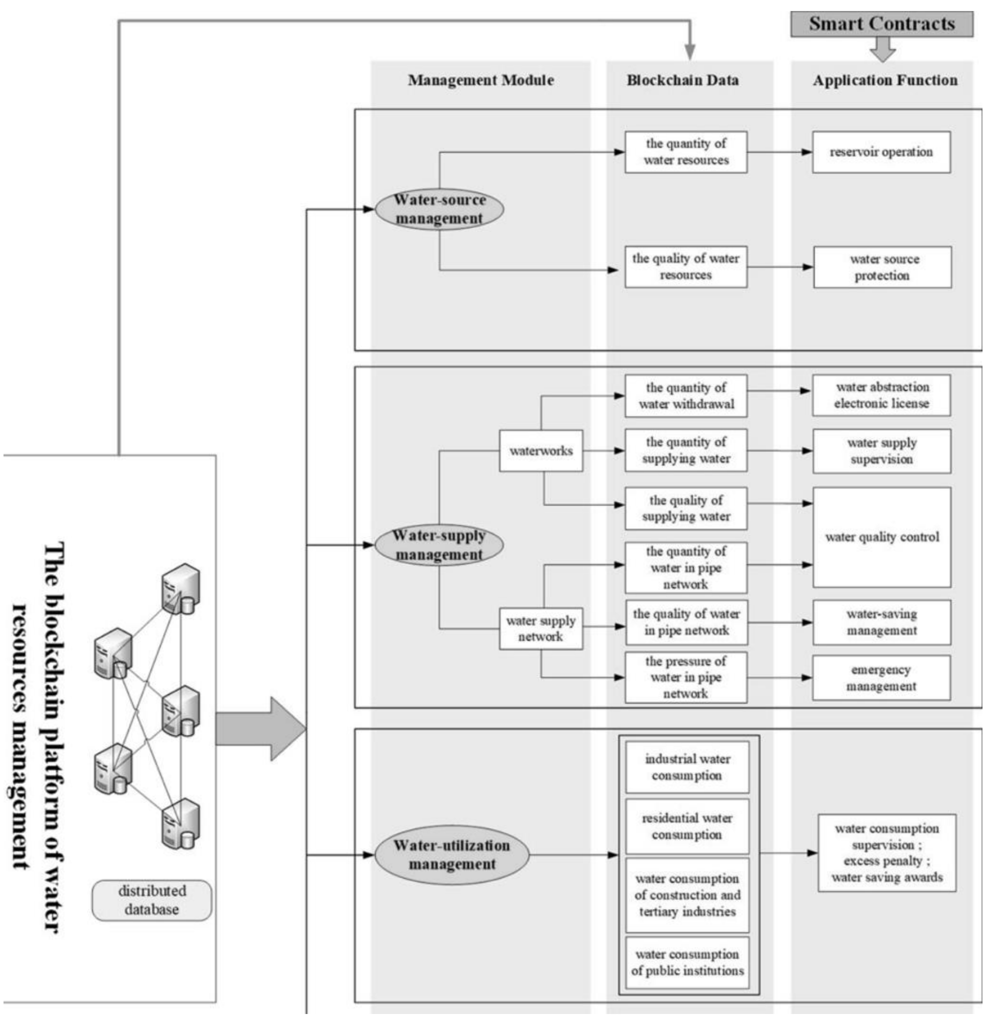


Figure 5: Visualization of how Blockchain can be implemented in water management divided into three different management modules [33]

Annex C: Green IoT and Infrastructure

Green IoT is an innovative process using software and hardware mechanisms in a more energy conscious way. This translates in creating connected devices which put a greater emphasis on reduction of power consumption, aiming towards maximum use of bandwidth and eliminating e-waste. To create a green IoT sensor, it must go through a precise innovative process considering green conception, utilization and recycle.[34]

Green IoT has several functions and applications, as can be seen in the graph below.

Figure 6: Green IoT/Smart-X Application [35]

Smart and green IoT – based on a mix of sensors, data analysis, and AI innovation – provides water information for farmers and businesses with the capacity to better monitor their water systems and the quality of the water supplied. This could lead to better decision-making. Furthermore, with less waste comes less consumption and hence a more sustainable preservation of water resources in the region.

In a nutshell, for the water management realm green and smart IoT such as these can help in several phases:

- → Reducing waste
- → Surveying water quality in the face of pollution and diseases
- → Bettering the efficiency of water systems
- → Building awareness of community utilization

Annex D: Case Studies for Multi-Criteria Analysis (MCA)

As part of the MCA, several case studies were identified which had successfully IoT and blockchain in water management and from which criteria could be derived. The case studies were the following:

Jordan Basin

The Jordan Basin has long been a source of tension, being one of the most critical sources of water for Israel, Jordan, and the West Bank. Due to the conflict, many communities in the West Bank suffer from lack of access to clean water, with 10% of Palestinian communities lacking access to drinking water[36] and "30% lacking access to basic sanitation facilities" [37]. This is mainly caused by non-sufficient and unsustainable water supply with root causes in underperforming infrastructure which cannot supply the required amount of water, ultimately resulting in non-Revenue Water (see Annex)[38]. The Accelerator Lab of the UN Program of Assistance to the Palestinian People, partnered with a start-up FlowLess to test a locally developed, low-cost, intelligent water leak detection system using IoT and Artificial intelligence[39]. FlowLess is able to bring together different innovators and experts in the fields of water technology, mechatronics, and software development. It aims to enable water utilities to accurately collect data and analyse the status, source, and location of leaks and losses in public water systems. The solution also helps service providers monitor water systems remotely during critical times when mobility options are limited. Experiments were conducted in Tammun and Ras Al-Falah in the Tubas province on the West Bank where they have worked together with e.g., Tubas' Joint Water and Wastewater Services Council (JSCWW)[40]

Based on this case study, the following criteria/ factors of success have been identified:

- → Private investment by a local start-up was the key factor for the project and for innovation
- → UN funding helped bridging innovation and development by empowering local people through the process
- → The project was implemented locally and aiming at a precise sanitary problem, thus not blocked by national difficulties of transboundary management

Mexico

In 2008 the National Autonomous University of Mexico (UNAM) initiated a program for the smart management and (re)use of water, called PUMAGUA. The program's main aims were to 1) detect leakages, hereby limiting potable water consumption by 50 %, 2) improve the quality of drinking water and wastewater and 3) promote efficient water use by the UNAM community[41]. By implementing Smart Water Management (SWM) technology in the form of remote water quality and water consumption measurement, the university decreased its water supply by 35% and significantly improved its drinking and wastewater quality. The lessons learned from this program were that 1) smart water management may build trust in consumers, 2) that SWM systems still demand a lot of effort to maintain and manage and 3) that financial resources are needed to acquire technological upgrades[42].

Based on this case study, the following criteria/ factors of success have been identified:

- → Private initiative was the motor of the project.
- → Sharing knowledge via university network represents the base of the viability of the project
- → Incentive to improve the quality of data regarding water management and quality are strong

Lake Victoria

The Flood and Drought Management Tools (FDMT)[43] project was initiated in 2014 by the Global Environmental Facility, and is supported by three international organizations (UNEP, DHI, IWA), in conjunction with local authorities regulating water basins. This project proposes to use SWM as a solution to better predict and manage uncertainty around transboundary water resources of Lake Victoria. The technical purpose of this project is to create an application that aggregates data on the basin water resource which is provided by satellite analyses (due to lack of means and confidence in on-site data). To ensure its sustainability, the project is based on a bottom-up approach, where the people's needs for the technology to be adapted were identified and there were feedback moments throughout the implementation. This has allowed for greater sharing of knowledge, which reduces the gap between international organizations and local communities. Through this frequent consultation of various actors and their needs, inclusion had a strong focus in the FDMT, and the realization of SDG 6 was the main priority.

Based on this case study, the following criteria/ factors of success have been identified:

→ Public investment from international organizations is key to implementing a project on transboundary water management.
→ High cooperation with local authorities such as water basins authorities is highly valuable for the sustainability of the project.
→ A bottom-up approach translated by adapting the technology to local communities needs and adjusting it via feedback is key for this project to last.
→ Water scarcity, lack of data, mistrust and mismanagement are fertile ground to implement blockchain and IoT in drinking water related projects.

Kenya (Hydro IQ)

HydroIQ was founded in 2017 in Nairobi, Kenya, as the world's first Virtual Water Network Operator (VWNO). It combines a range of smart/automated metering devices into the existing traditional water supply network on household level, thereby allowing local consumers to only pay for the water they consume[44]. This is especially significant for Kenyan households, where water constitutes of 11% of their income but due to unmetered consumption and leakages, they only receive 50% of the water which they pay for[45]. By combining sensors, data analytics, and mobile and online payments which all operate through Blockchain, HydroIQ creates total transparency in how water is managed. Their clients are not involved in the technical specificities of IoT and blockchain but are rather aware of the utilization of these technologies in how they can manage their own water. HydroIQ is planning on expanding as VWNO into new regions, including Nigeria, South Africa, and Guatemala, but remains small-scale with a community-based approach. This is partly due to lack of large-scale investments which allow them to expand, from both government and private actors[46].

Based on this case study, the following criteria/ factors of success have been identified:

→ Private initiatives can be quickly implemented and are functional in water management.
→ Digital infrastructure is necessary for implementing blockchain and IoT in water management.
→ Government support through investments is preferred when aiming to grow, however, it is not an absolute necessity.
→ A demand for more efficient water management is necessary which is born from a certain degree of water uncertainty.

Australia

Water Ledger is a platform developed in 2020 by Australian blockchain company Civic Ledger in collaboration with the Cooperative Research Centre for Developing Northern Australia (CRCNA), RMIT's Blockchain Innovation Hub, SunWater, and other project partners. The trading platform allows the system to make top-level pricing data publicly available, while maintaining the confidentiality of financial transactions. Thus, market participants have access to supply chain information in real-time. This is only possible because of the strong legal framework surrounding water rights in Australia, which enables the allocation of water rights to individuals which are then registered in blockchain as 'water tokens'[47]. Furthermore, Australian province governments play a large role in financing blockchain in water management, with Civic Ledger having their initial financing come completely from Queensland authorities[48]. The management of water rights using blockchain is facilitated by strong climatic and hydrological models which provide enough data which can be fed into blockchain to make water management using blockchain possible.

Based on this case study, the following criteria/ factors of success have been identified:

→ Investments from the public sector in private initiatives for water management using blockchain is necessary for these initiatives to become established and operate on larger scales.
→ Climatic and hydrological modelling is a prerequisite for being able to manage water with blockchain, there must be data available.
→ Strong infrastructure, both physical and digital, aids in being able to quickly implement water management initiatives.

Annex E: MCA and Results

Based on the above-mentioned case studies, several criteria, sub-criteria, and corresponding scale were established. These are the following:

Tab 1: Multi-criteria analysis definitions

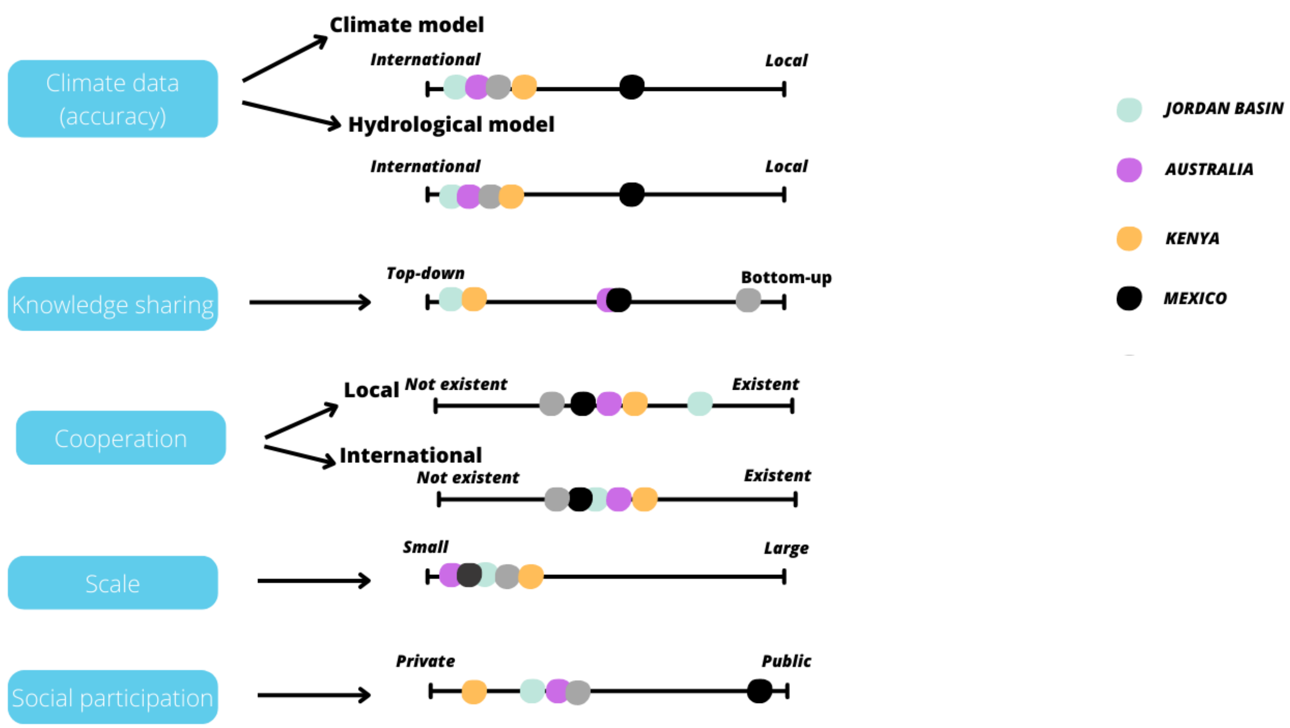
Criteria	Definition	Sub-criteria	Definition	Scale	Definition
Government support	*How water management using blockchain and IoT is facilitated and supported by the government through law and financial means.*	Financial	*Quantity of financial aid provided by the government towards frontier technology in water management related projects.*	Limiting	*Financial policy of governments is a burden on initiatives which want to implement technology in management of natural resources, e.g., taxes.*
				Aiding	*Financial policy actively helps the above-mentioned initiatives, e.g., subsidies.*
		Regulations	*Amount and quality of regulations provided by the government towards frontier technology in water management related projects.*	Limiting	*Laws and existing policy surrounding management of natural resources does not allow for introduction of technological solutions/ blockchain specifically.*
				Aiding	*The legal/ policy framework is strong enough to be reliable and allows for management of natural resources through technological solutions.*
Investment	*What financial means are available for implementation of blockchain and IoT in water management and who is providing these financial means.*	Private	*Amount of private investment in frontier technology for water management and in water management projects.*	None	*There is a complete absence of private investments which are available.*
				Abundance	*There are no difficulties for initiatives in obtaining investments from the private sector, and investment climate is extremely positive and stimulating.*
		Public	*Amount of public investment in frontier technology for water management and in water management projects.*	None	*There is a complete absence of public investments which are available.*
				Abundance	*There are no difficulties for initiatives in*

					obtaining investments from the public sector, and investment climate is extremely positive and stimulating.
Water uncertainty	*That which determines the demand of people/ government for more efficient and better water management.*	Security	*Water availability regarding thresholds of drinking water security*	High	*Water is readily available to meet the demands of the population and there is no difficulty in obtaining water when necessary.*
				Low	*Water availability is not able to meet the average demand of the population.*
		Quality	*Water availability regarding thresholds of drinking water quality*	High	*All water which is available is of high quality and is drinkable.*
				Low	*The water which is available is not of drinkable quality, and people must put considerate effort into obtaining drinking water.*
Climate data availability	*What data is available on water and climate change can influence what data is used for blockchain water management.*	Climate models	*Applicability and relevance of available climate models for water management projects.*	International	*Available climate models are only on international level with little focus on local conditions.*
				Local	*Available climate models provide data on a very local and case-by-case basis.*
		Hydrological models	*Applicability and relevance of available hydrological models for water management projects.*	International	*Available hydrological models are only on international level with little focus on local conditions.*
				Local	*Available hydrological models provide data on a very local and case-by-case basis.*
Knowledge sharing	*Way of sharing knowledge in the implementation of water management related project*			Top-down	*A top-down approach is when a technology is implemented by one entity without the knowledge of it being shared.*
				Bottom-up	*A bottom-up approach consists of sounding out the needs and the knowledge of the local population beforehand the process. And*

					integrating feedback throughout the implementation of the project and after the technology has been settled.
Cooperation	*Those who are involved in the decision-making process.*	International	*The process of decision-making involves international agents and is seen as a matter of international importance (because of transboundary water management of conflict).*	Non-existent	*There is no international cooperation.*
				Existent	*All decision making is done by international actors.*
		Local	*The process of decision-making involves only small-scale, directly affected, and local stakeholders.*	Non-existent	*There is no local cooperation.*
				Existent	*All decision making is done by local actors.*
Scale	*Scale of implementation for water management project.*			Small	*Small scale of implementation means the project is in one area (a village or a source of water).*
				Large	*Large scale of implementation is a national scale or international scale. It is when the project is applied to more than one water source.*
Social participation	*How people affected by water management using blockchain and IoT are involved in the decision-making process surrounding implementation.*			Private	*Only the clients of private businesses incentives are involved in the decision-making process.*
				Public	*There is community-wide involvement in decision-making, even when it regards private business incentives.*
Infrastructure	*The infrastructure which is needed for implementation of IoT and blockchain in water management*	Physical	*Infrastructure which is necessary for water management*	Non-existent and no maintenance	*There is no physical infrastructure for water management and there is no maintenance there to create it.*
				Existent with maintenance	*The physical infrastructure for water management is there and there is maintenance to keep*

					it on an adequate/ high functional level.
		Digital	*Infrastructure which is necessary for implementation of blockchain/ digital tools*	Non-existent and no maintenance	*There is no digital infrastructure for water management and there is no maintenance there to create it.*
				Existent with maintenance	*The digital infrastructure for water management is there and there is maintenance to keep it on an adequate/ high functional level.*

The case studies were placed on the scales for every criteria/ sub-criterion to be examined what contributed to their success: *(If there is no dot for a case study, there was not sufficient data on that criteria to make a validated and solid conclusion).*



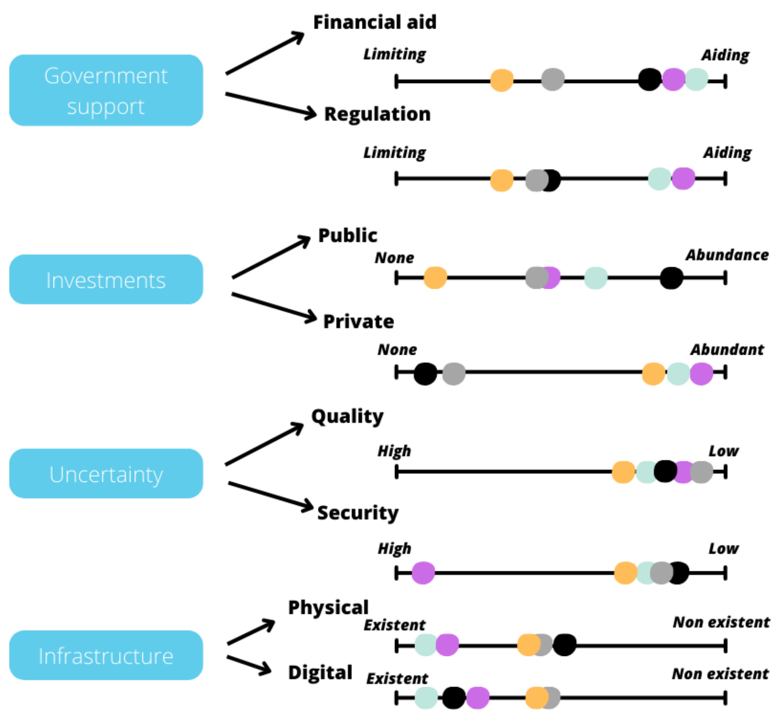


Figure 7. Multicriteria Analysis (yellow = Kenya; black = Mexico; purple = Australia; blue = Jordan Basin)

The criteria were also applied to the examined case studies (Libya, Darfur, and Viet Nam; Annexes F, G, and H respectively). This resulted in the following placement on the scales for every criteria/ sub-criterion:
(If there is no dot for a case study, there was not sufficient data on that criteria to make a validated and solid conclusion).

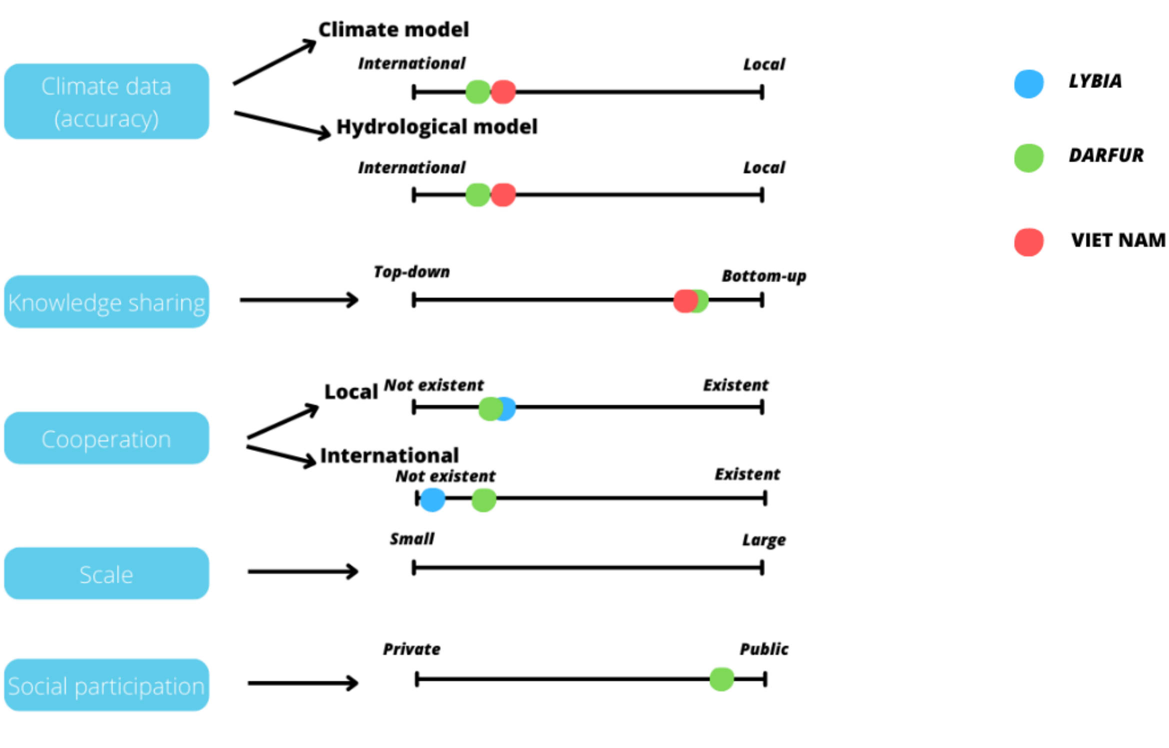


Figure 8: Multicriteria Analysis (blue = Libya; green = Darfur; red = Viet Nam)

From the first scales, the following conclusions can be made:

→ Water uncertainty is the main incentive for the implementation of blockchain and IoT in water management.
→ Private investments play a key role in supporting water management incentives, but there must be some degree of public support in the form of financial and regulatory help.
→ To be able to implement blockchain and IoT in water management, there must be physical and digital infrastructure which can support it. This infrastructure must be maintained and reliable.
→ Cooperation should always be there, but it is not necessary to have cooperation on intense levels at both international, national, local, community-based, etc., level.
→ Small scale is seen as a factor of success in the current implementations of blockchain and IoT in water management.

From the scales applying it to new case studies (Libya, Darfur, and Viet Nam), these conclusions can be made:

→ Even though there is support from public investments, private investments are lacking significantly,
→ There is high uncertainty of water which can be seen as a solid incentive for alternative water management systems using blockchain and IoT.
→ Infrastructure is lacking or not maintained in both physical and digital domain, which can be considered a limiting factor in implementing blockchain and IoT water management.
→ There is little cooperation on all levels of society, which could be a limiting factor for implementation but does not directly mean it is impossible (based on the conclusions of previous case studies).

Annex F: Application MCA to Applied Case Study Libya

In Libya, there has been a protracted humanitarian crisis and conflict with its origins at the beginning of the Arab Spring in 2011. The protests led to civil war, foreign military intervention, and the death of Muammar Gaddafi, the previous leader of Libya. The conflict and instability which followed caused several significant water cuts and water management systems were heavily impacted, affecting millions of people across the nation[49]. "The repeated attacks on the Manmade River systems caused about 190 wells to be rendered out of service, bringing this vital sector to the brink of collapse"[50]. Since then, there has been systematic mismanagement of water with no central government who is able to oversee it, combined with a looming and severe water scarcity with less than 56mm of long-term average precipitation annually[51].

Because of these characteristics, Libya was analyzed based on the before established criteria to assess if it is likely that Blockchain and IoT for water management can be implemented.

Government support

Regulation on water is the responsibility of the Ministry of Water Resources (MoWR) and Ministry of Economy (MoE) of Libya. However, whilst there are regulations, there is no central authority on the ground who is enforcing them and impose the penalties as stated in the regulations[52]. Furthermore, water in Libya is heavily subsidized, with an average rate of 0.15US$/m3 for domestic use which is below the regional average of 0.75US$/m3 and the global average of 2.04$/m3[53].

Investment

"Libya relies mostly on public sources to fund its water resources projects"[54]. The private sector's share is insignificant, and mostly limited to bottling drinking water[55]. The public investments in water management and sanitation per capita was US$ 0.05, compared to US$15.66 per capita as regional average, with no investment made in river basin development and irrigation finance[56].

Water uncertainty

There are several factors contributing to water scarcity in Libya, including the following: "(1) Excessive groundwater exploitation; (2) Decreased annual average of rainfall; (3) Intensive agricultural activities in the coastal plains; (4) Seawater intrusion; (5) Low water tariffs; (6) Lack of institutional framework; (7) Lack of clear strategy related to the local water sector; (8) Lack of awareness in the public of the need of rational use and management of water resources; (9) Poor management in the General Water Authority"[57]. All this combined has led to Libya being the sixth water poorest country worldwide[58].

Climate data availability

N/A

Knowledge sharing

N/A

Social participation

N/A

Infrastructure

Libya is largely dependent on dams, aquifers, and desalination plants for its water supply. The first two are located inland, whereas the demand for water is highest near the coastline where most of the population lives[59]. However, due to poorly maintained water infrastructure network, there is large amount of water loss between 35 and 50%[60]. Digital infrastructure is well developed in coastal urban areas but lags in Libya's southern region[61]. However, COVID-19 has accelerated digitalization of Libya and has contributed to it being a priority for Libyan government to invest in[62].

Cooperation

Libya has no cooperation with its neighboring countries with regards to surface water resources[63]. Within Libya, there is a multitude of societal stakeholders which are expected to cooperate with regards to water management. The MoWR, MoE, Ministry of Education (MoEd), UN partners, private sector, and local NGOs are all stakeholders which must cooperate[64].

Annex G: Application MCA to Applied Case Study Darfur

In 2003, conflicts in Darfur intensified, not only over ethnic and religious issues, but also over natural resources, including water. Darfur is an example where the scarcity of drinking water and conflict are intertwined[65]. Indeed, water is becoming increasingly scarce in Sudan, the demand is increasing in some regions (due to migration due to the conflict), and the supply is decreasing due to the climate change (flood and droughts)[66]. The water is hoarded by the parties in power (the government and the Janjaweed, an Arab militia which are currently in power). These categories of people use their position in society to deny access to water to minorities (Masaalit, Zaghawa...). [67] This strong competition for natural resources is fueled by the uncertainty caused by climate change. Water, including groundwater, is becoming less and less consistent, and the remaining water is unclassifiable. Finally, out of 49 recorded conflicts that took place in Darfur during the period 1950-2010, competition over water caused more than 75%.[68]

Because of these characteristics, Darfur was analyzed based on the before established criteria to assess if it is likely that Blockchain and IoT for water management can be implemented.

Government support

Thus, it is easy to say that better water management is crucial for Darfur[69]. Indeed, policies on water consumption and distribution have been ignored or poorly enforced since 2003.[70][71] Moreover, it is underlined that the government contributes to the segregation of its population regarding access to water, due to the ethnical and religious conflict. [72].

Nevertheless, with the influence of international community, several projects have been put in place to improve the current water situation in Darfur, with the help of the Government. For example, the Wadi el ku project started in 2018, funded by the European Union, was implemented by UN Environment in partnership with the government of Sudan, the state government of North Darfur, local-based civil society organizations and local communities.[73] Moreover, the government created a National Council for Water Resources to lead actions for water management at a national level.

Investment

Investment in the water sector is present in Darfur aiming towards better access to drinking water and a resolution of conflict via the better management of natural resources. Thus, international organizations such as the UNEP and World Bank invested in water related projects in Darfur. According to the African Development Bank report published in 2016, the WB invested $1.8 million in a peace building for a development project.[74] Moreover, countries such as the EU, the US, the UK, Japan, or China, also invested in water related projects in Darfur.[74] For example, the Japan International Cooperation Agency invested $1.7 million in a Human resource development project, the government of China provided bulk water supply in Nyala, and the UK invested GBP 10.5milion for urban water supply improvement interventions in the state capitals. More locally, the African Development Bank (African Water Facility) invested $4.5 million in the Darfur Water project in 2012.[74]

Water uncertainty

Darfur is semi-arid or arid, its water resource mostly comes from groundwater. Darfur's water resources are critical for several reasons. On the one hand, climate change exacerbates water uncertainty. Indeed, not only is water becoming scarcer with global warming, but also, extreme events such as droughts and floods that hit Darfur are becoming more and more frequent and uncontrollable. On the other hand, the existing water reserves are often inaccessible and far from the living aeras. Moreover, in Darfur there is a situation of saturation of the water market. Indeed, the quantity offered is not increasing (or even decreasing with climate change), and demand is becoming tense due to migration flows that avoid conflict zones. Thus, these two main reasons mark the lack of water in Darfur. They are together with poverty, growing social tension, growing urbanization and the weakening of political institutions, factors of high-water uncertainty in Darfur.

Climate data availability

There is a basis of climate data available for Sudan in general. In fact, the RIMA baseline report (2020) identified a number of shocks and stressors impacting the resilience of livelihoods in Sudan. Moreover, the climate research unit of the University of East Anglia worked on a set of data used in the climate change knowledge portal for development practitioners and policy makers (World bank group)[75].

Knowledge sharing

Knowledge sharing is becoming more present in Sudan because of several bottom-up projects put in place by international organization. For example, the Wadi el ku project started in 2018, launched by UNEP. The aim of this project is to involve the different actors with conferences (with a special focus on women), to understand the need of the population, and the current state of water management in the aera. It gathered more than 50 actors around the table to discuss how to transform the river in community-built weirs. The goal was to build dams so that water would be retained and then distributed between farmers and drinking water. Nevertheless, this project was sabotaged by farmers who felt neglected.[76] This project could have been completed by the blockchain, which brings trust and transparency to the data, so that the different parties can see the consolation of the others.

Social participation

Social participation is mostly community based. In fact, a lot of people demonstrates in the street claiming access to drinking water. Thus, big community-based project like the 'Wadi el ku' trying to include different actors mixing back groups and affiliations exist, but there is also small community-based project, which lack of inclusiveness[77]. Moreover, communities in Africa are trying to develop co-management regimes regarding natural resources. By doing this, they want to combine the benefits of local decision making over natural resources with formal legal frameworks.

Infrastructure

Considering the Darfur Joint Assessment Mission (DJAM) in 2013, a review of Darfur's infrastructure was made. This report indicates that the state of infrastructure in Darfur is very poor and inadequate. [78]

First, an important reform of the legal framework of the region must be put in place to convey towards a better water management. In fact, even if the government created structures, it is far away from the field reality. [79]

Second, there is infrastructure available (even if it is not enough), but the one in place are not functional (30% of the hand pumps in Darfur are not functional). They are not functional because of technical problems (lack of maintenance) but also because of destruction.[80] Thus, Darfur suffers from a lack of investment in infrastructure in the water sector, these investments are needed to do maintenance and to increase the quantity of infrastructures. However, the Dams Implementation Unit of the Ministry if Water Resources and Electricity underlines that there are other challenges than the lack of investment such as the insecurity and the lack of basic information.[81]

Third, there is not constant eelectricity provision in Darfur. In fact, this region is not linked to the existing power grid system of Sudan. The electricity is generated from smaller private generators at very expensive rates for the communities. Thus, to implement blockchain and IoT the electricity system will be a challenge.

Cooperation

At an international level, Sudan is part of the Nile Basin water management. It means that Sudan is part of a larger picture when it comes to this natural resource. Moreover, Sudan shares aquifers with neighboring countries for the groundwater resources.[82] Thus, the country can't make its selfish choices and has to consider transboundary management.

At a national level, Sudan is divided in 18 States, each sub-divided into localities, each sub-divided into administrative units. This makes cooperation very important and difficult to reach. Plus, the population itself tends not to cooperate due to the conflict and the segregation of people due to their ethnic group or religion.

Scale

- NA

On the one hand, the insecurity of water resources and climate change are pushing the different actors to find a solution. The blockchain could be applied here because it is decentralized and does not depend on a party that has a monopoly of power. In addition, it brings transparency and trust in data, and makes information accessible to all.

However, blockchain, while being promising on paper, does not appear to be the easiest solution to apply according to our criteria, to provide access to drinking water. Indeed, the government appears to be a brake on the implementation of water policy[83]. What's more, the local newspaper Dabanga[84] stresses that people know that the pumps are broken but that the problem is not getting the information. The problem is in the action performed after having the information. Plus, blockchain requires energy and digital infrastructure, which are not developed in Darfur.

<u>Annex H: Application MCA to Applied Case Study Viet Nam</u>

An important part of Vietnam's population resides by it's the major water basin namely Thai Binh, Mekong Delta and Dong Nai. However, poor physical infrastructure and low financial investment result in low utilization.

In addition, the uneven distribution of precipitation has caused nationwide lacks, and the prospects of climate change (CC) predict that this trend will continue to increase. Finally, fast industrialization has led to the toxicity of water resources. As a result, solely 39% of the population can obtain safe water and sanitation services. Below is a summary review of the Donnay case study against the criteria.

Government support

The Vietnamese government has made improving water management a top priority, but fast development and technological and economic growth have created multiple externalities, including declining water quality. The World Bank has made recommendations to improve the management and financing of these limited water resources in the face of climate change, highlighting the need for stronger regulatory enforcement and oversight. There is also a clear lack of local management and incentives to promote mitigation (such as carbon offsets)[85]

Investment

"According to Sai Gon Water Supply Corporation - SAWACO investment in HCMC for W&WW infrastructure will be approximately 700 million USD by 2015"[86].

Water uncertainty

According to Noi & Nitivattananon , "about 3.9 million people in Viet Nam are projected to experience water stress by 2050" [87]. Noi & Nitivattananon furthermore state that Viet Nam also "ranks among the top five most impacted countries with regard to sea level rise"[88]. "CC-related risk was not assessed based on the main components as adaptive capacity, hazards, and vulnerability" [89].

Climate data availability

Aalst, Cannon & Burton have stated that "it is much more difficult to predict what will happen to smaller-scale atmospheric phenomena as well as get a confident or accurate prediction of local risk" [90].

Aalst et al claim that "it is difficult to interpret conventional CC projections for small areas involved in CC risk assessment", as in general, "CC can be projected relatively well for large areas with regards to change in average temperature and, to a lesser extent, change in precipitation"[91].

"There has been very little systematic effort in conducting CC risk assessment at local level and in particular the tools/techniques that can be applied to show clear interaction among three main components of CC risks such as hazards, vulnerabilities, and adaptive capacity at local level" respectively[92].

The UNFCC states that predicting the evolution of small-scale atmospheric phenomena and obtaining reliable and accurate predictions of local risk is much more difficult. Traditional CC projections are difficult to interpret for the "small areas involved in CC risk assessment". In general, CC is relatively well projected over large areas in terms of the magnitude of mean temperature change and precipitation change. Few systematic efforts have been made to conduct CC risk assessments at the local level.[93]

Knowledge sharing

Aalst et al state "unlike other key issues of development, there is very little grassroots awareness or campaigning on issues of climate change"[94].

Social participation

N/A

Infrastructure

"Water infrastructure in Dong Nai River Basin (DNRB), especially in Ho Chi Minh City, is "seriously overloaded" as the city has become a very dense population" [95]. The studies on W&WW infrastructure in the context of CC were not investigated at community level"[96].

Cooperation

N/A

Scale

N/A

Annex I: Smart Water Management (SWM)

SWM "is a way to collect, share and analyze data from water equipment and water networks" [97]. It uses IoT in the shape of sensors and monitors (data sharing tools) to optimize the knowledge on water management. SMW provides up-to-date information and allows users to access solutions to better manage their resources.[98] SWM can be a way to change conventional water management system into interconnected system which can have the ability to analyze a situation and provide a quick response. It appears to be cost-efficient, and timesaving.[99] For water supply, SWM tools are used in four principal ways: "to collect and transmit information in real time; to process information and remotely operate and optimize systems and processes […] and to store, use and report data" [100].

SWM has the potential to enable better management of water in areas where there is water scarcity because it is very flexible and can be adapted to the project's scale (whether it is aimed at a city like Mexico, or a transboundary basin like in the case of Lake Victoria). Moreover, using smart water technology enables project managers to limit the need for infrastructure and it allows for more data to be collected and shared. Consequently, it may be used to adapt policy decisions by reducing the uncertainty of the resource availability due to climate change, thanks to up-to-date data and satellite observation. [101]

Annex J: Global Drinking Water Standards

Safe drinking-water is considered to be water which does not create significant risks to health during consumption over the whole lifetime of the person consuming it [102]. However, due to chronic mismanagement, misuse, and overextraction, fresh- and groundwater supplies have become increasingly contaminated directly effecting drinking water quality [103]. Below is a representation of different parameters adhered to around the world with regards to drinking water quality parameters:

Parameter	WHO	NAFDAC	FMENV/DPR
Temparature (^{0}C)	24 -30	-	24-28
pH	6.5-8.5	6.5-8.5	6.5-8.5
Conductivity (μS cm^{-1})	1200	1000	1000
TDS (mg/L)	250-500	500	500
Hardness (mgL^{-1})	100-500	100	100
Alkalinity (mgL^{-1})	200	200	200
BOD_5 (mgL^{-1})	4	4	4
Cl^- (mgL^{-1})	100-500	100	200
NO_3^- (mgL^{-1})	10-50	10	10
PO_4^- (mgL^{-1})	0.5	0.5	0.5
Mn (mgL^{-1})	0.4	-	0.2
Pb(mgL^{-1})	0.01	0.4	0.4
Fe(mgL^{-1})	1-3	1.0	1.0
Co(mgL^{-1})	0.05	0.05	0.05
Cd(mgL^{-1})	0.05	0.05	0.03

Figure 9: Drinking quality parameters

Annex K: Abbreviations and Glossary

Abbreviations:

UNCTAD = United Nations Conference on Trade and Development

GHG = greenhouse gases

IoT = Internet of Things

MCA = multi-criteria analysis

E-waste = electronic waste

AI = artificial intelligence

SWM = smart water management

FDMT = flood and drought management tools

VWNO = virtual water network operator

WB = World Bank

DJAM = Darfur joint assessment mission

Glossary:

IoT = a network of sensors and other smart devices which collectively share data to one centralized data storage point.

Blockchain = a shared, immutable ledger that facilitates the process of recording transactions and tracking assets. .[104]

Water scarcity = when there are insufficient freshwater resources to meet the human and environmental demands of a given area. It is a relative concept.[105]

Water management system = a collection of devices, improvements, or natural systems whereby surface- and groundwater is conveyed, controlled, impounded, or obstructed.[106]

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