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RESEARCH ARTICLE

Leveraging Big Data Analytics to Enhance Water, Sanitation, and Hygiene (WASH) Systems

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Highlights

- Big data analytics enhances WASH systems using tools like Apache Hadoop and Spark.
- ICT solutions improve data collection, monitoring, and decision-making in the WASH sector.
- Social accountability and open data promote transparency in governance for WASH services.
- Big data supports sustainable resource management and equitable WASH service expansion.

Abstract

The Water, Sanitation, and Hygiene (WASH) sector is crucial to public health and achieving sustainable development goals. To enhance the effectiveness of WASH initiatives, it is essential to gather data from various sources, including Flow Monitoring, Water Point Mapping (WPM), mWater, Leak Detection (FMLD), and mWash. By implementing big data analytical tools such as Apache Hadoop and Apache Spark, this sector can efficiently store, process, and analyze large volumes of unstructured data within a distributed, parallel computing environment. Leveraging big data analytics in the WASH sector enables improved monitoring, visualization, equitable data-driven decision-making, post-implementation tracking, open data practices, and strengthened social accountability, ultimately supporting the sector's development and sustainability.

Keywords: *Apache Hadoop; Apache Spark; Cluster Computing; Social Accountability; E-governance*

Introduction

Big data draws relevant information from a variety of sources, often containing data in multiple formats. Rooted in computer science, big data refers to vast amounts of information collected through advanced technologies that cannot be efficiently processed using traditional computing methods. It is a transformative technology in the field of information technology, characterized by the rapid increase in data variety, high speed of data generation, and large volumes, making it challenging to analyze with standard analytical tools. It is the challenge to implement big data analytical tools and techniques in the field of WASH sector.

The volume of big data is expanding rapidly, ranging from a few terabytes to multiple petabytes [1]. It encompasses structured, semi-structured, and unstructured datasets, with a strong emphasis on unstructured data [2]. Big data requires a variety of tools, techniques, and technologies to handle these vast and complex datasets, enabling the production of detailed insights [3]. Insights gained from big data analysis are crucial, and the concept of "big data" has become highly prominent within the field of information technology. It is applied across various sectors, including government, transportation, education, healthcare, and smart city projects [4]. Michalik et al. [5] introduced big data in the education sector, developing a technical architecture and

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employing software applications to enhance educational performance. Big data is defined by six key characteristics, known as the "six V's"—velocity, volume, variety, veracity, variability, and value [6]. Currently, WASH sectors are also generating huge amount of data from different sources. But, a scanty of research that has successfully implemented big data analytics in WASH sector to achieve the results using key characteristics of big data.

Big data presents challenges in areas such as storage, sharing, capturing, searching, transferring, analysis, and visualization [7]. Big data analytics involves gathering, storing, organizing, processing, analyzing, and evaluating large data sets to uncover meaningful patterns and extract valuable information [8]. This approach helps organizations understand crucial insights within the data and supports informed decision-making, particularly in critical situations. Companies increasingly use big data analytics [9] to enhance efficiency, boost sales, improve customer service, streamline business operations, and manage key risks. One of the main challenges in big data analytics is effectively applying new analytical tools and techniques to existing or incoming data to drive data-based decisions. Big data analytics addresses the limitations of traditional business intelligence and analytical tools by enabling the processing of massive datasets, helping organizations collect data, identify new opportunities, cut costs, make faster and better decisions, and develop innovative products and services [10]. Still there is adequate work in the field of WASH for manipulation of variety of data from different sources to get results by the use of big data analytical tools and techniques.

Alencar et al. [11] introduced iEnvironment, an application designed for monitoring and modeling surface water using big data. They described its architecture, highlighting its reusability and flexibility. Ping et al. [12] proposed a scene analysis framework for the Water Resources Data Center (WRDC) aimed at organizing information within a big data environment, enabling rapid processing and dynamic analysis of water resources. Chalh et al. [13] explored the concept of big data for environmental science, focusing on water resources, and presented the architecture of a Water Resource Management system built on a Big Data Open Platform. Zhang et al. [14] developed methods for clustering and classifying navigational aids using big data to establish a scientific classification system, reducing reliance on subjective interfaces. Suciu et al. [15] proposed a water environment monitoring system for underwater and surrounding areas, offering a platform interface for end-users to visualize water environment events in real time. Some of the authors have worked on monitoring and modelling system for under water and surrounding areas to visualize water environment in real time using big data. As data are growing rapidly in WASH sector in recent time and to handle such a huge amount of data, a big data analytical tools will be the better option for the manipulation of data to provide good results for the decision makers in WASH sector.

Bothwell and Hellen [16] explored the use of information and communication technology in emergency response, education, health, agriculture, water, and sanitation, demonstrating that technology enhances learning and program delivery. Ameca et al. [17] introduced an autonomous robot to aid in the cleanup and preservation of lagoons; this robot navigates along the edges of water tanks and utilizes a network to collect solid waste. Habiba et al. [18] examined the needs of a big data-based access control management system, creating dynamic policies based on permission and access control rules. Chen and Zhu [19] developed an intelligent control algorithm to optimize fast and efficient network data transmission, focusing on energy consumption in sanitation system monitoring projects. Suakanto et al. [20] created a tool for local governments to monitor city conditions, including temperature, air and water pollution, and traffic, through information communication technology. By the use of traditional system, local government used to monitor city conditions, temperature, air and water pollution. But if they will implement big data analytical tools and techniques, government will analyze the data faster to foster the services to the citizens.

Big data has numerous impactful applications in health sciences. Huang et al. [21] reviewed recent uses of big data, including healthcare recommendation systems, sensor-based food safety monitoring, and health condition tracking, as well as the future of health sciences in the big data era. Duan et al. [22] introduced a nursing care recommendation system to support clinical decision-making, quality control, and nursing education. By integrating sensors with hardware and software, a range of applications has emerged to monitor food safety and health conditions. High-tech companies have introduced products like smart chopsticks [23], which can measure pH levels, calories, temperature, and cooking oil freshness, and the Apple Watch [24], which tracks heart rate. Zheng et al. [25] gathered air quality data from major cities in China by combining information from monitoring stations with other sources. Authors have implemented big data in different sectors like health care, safety monitoring, health condition tracking, nursing care, recommendation system, food safety, but they fail to implement big data analytical tools to implement in WASH sector.

The objective of the article is to explore the transformative impact of big data and information communication technologies (ICT) across various sectors, with a particular focus on the Water, Sanitation, and Hygiene (WASH) sector. It aims to detail the applications of big data analytics in improving water resource management, sanitation, and hygiene services, and highlights innovative ICT solutions that enhance data collection, reporting, monitoring, and decision-making. Additionally, the article discusses the components of big data analytics, such as Apache Hadoop and Spark, and emphasizes the importance of open data, social accountability, and sustainable practices in utilizing data for equity and effective governance. Ultimately, the article seeks to underscore the role of big data in enabling efficient, transparent, and impactful decision-making that addresses critical societal challenges.

Innovative ICT Solutions for the WASH Sector

Information and communication technologies (ICT) have been applied across various sectors, including the WASH (Water, Sanitation, and Hygiene) sector. In this context, mobile phones, software applications, web platforms, geographic information systems (GIS), and sensors are being utilized. This article introduces the use of big data analytics in the WASH sector, highlighting its value for water resource management and the improvement of sanitation and hygiene services.

Participation via Mobile Platforms

1) HueWACO

HueWACO is a large semi-autonomous water utility located in the Hue province of central Vietnam [26]. Operators at HueWACO's satellite treatment plant regularly collect water samples from the distribution network. Data from these samples are traditionally recorded in handwritten logbooks and then sent to the Quality Assurance Manager at the central laboratory for review. In this project, mobile data technology is being introduced to streamline and enhance the reporting process.

2) Teuk Saat

Teuk Saat, a nonprofit organization, provides clean drinking water to rural communities in Cambodian villages [27]. Guided by values of accountability, sustainability, health, relationships, and empowerment, its operators conduct basic water quality tests, recording data in logbooks. Staff from the central office visit rural sites to offer technical support and gather these logbooks monthly. However, this process of collecting and reporting test results has proven to be time-consuming. To improve efficiency, Teuk Saat's management has implemented a mobile application for streamlined collection of test results and sales data.

Fig. 2. Distribution of bottled water

3) MajiVoice

Majivoice is a software application developed to enhance water services in Nairobi by utilizing customer feedback reports[28]. Previously, Nairobi Water had limited direct interaction with its customers. However, as the demand for water grew, the company began engaging more actively. Through the mobile app and website, customers can report issues and ask questions, allowing staff to address complaints directly. This system has strengthened participation, responsibility, and responsiveness, transparency, accountability within the company.

Fig 3. Software Application for Water Services

A. mWASH(Missional Water, Sanitation, Hygiene)

The mWASH mobile application is designed for the Water, Sanitation, and Hygiene (WASH) sector, aiming to address critical global challenges in water access, sanitation, and hygiene [29]. This app plays a role in decreasing waterborne diseases by an estimated 65% through promoting essential hygiene and sanitation practices, principles of transformative development, and strategies for encouraging positive behavioral change.

MajiVoice : Select Category
1. Billing / Cost
2. No Water
3. Water Quality
4. Water or Sewer Leak
5. Meter/Connection
6. Corruption
7. Other...

Fig 4. Mobile Application for WASH

B. mWater

mWater is a application of mobile-to-web platform, used globally for monitoring and managing water systems. Active in over 130 countries, this app supports mapping, tracking water and sanitation conditions, and conducting mobile-based surveys while fostering collaboration with local governments. By leveraging data collected through mobile devices, mWater has facilitated the development of various services that enhance operational efficiency and enable effective monitoring of water systems. The accessible data empowers decision-makers to make timely, informed decisions.

Fig.5. mWater - Web Platform Application

C. Water Point Mapping (WPM)

Determining the location of water infrastructure and gathering related data involves using specific technologies [31]. The information collected serves as a foundation for further analysis. Water Point Mapping (WPM) is employed to track the condition and distribution of water points, enhancing water supply coverage. Additionally, WPM provides a reference for assessing water supply coverage and reporting on sector performance.

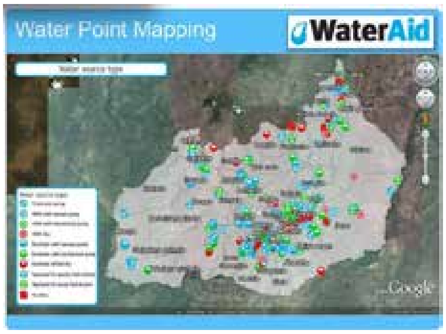

Fig. 6. Geographically Water Point Mapping

D. Flow Monitoring and Leak Detection

Water supply organizations frequently encounter issues with unintended water leakage caused by rust, breaks, damage, or faulty pipes. Since water supply networks are typically installed underground, detecting and monitoring leaks can be challenging. Information technology offers solutions to enhance oversight of drinking water systems. Through telemetry, measurements and data from remote locations are transmitted to receiving devices, enabling continuous monitoring and assessment [32].

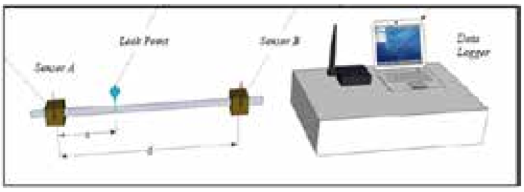

Fig. 7. Flow Control and Leak Detection

Framework for wash sector information using big data analytics

The conceptual outline of big data analytics aligns with that of traditional analytics or business intelligence projects; however, key differences lie in the processing methods. Traditional analytics often utilize basic tools on standalone systems to complete analyses. In contrast, big data analytics distributes data and processing tasks across multiple nodes. While distributed and parallel computing have been around for decades, their use in big data processing is relatively new for companies aiming to make rapid, informed decisions and achieve strategic goals. The rise of open-source platforms like Hadoop and Spark has further encouraged big data analytics adoption across various fields. Although classical business analytics tools tend to be more user-friendly and transparent, big data analytics tools are generally more complex, require programming skills, and often need expert handling. Figure 8 illustrates the main components of big data analytics within the WASH sector.

E. Big Data Sources

Big data inputs are gathered from a variety of internal and external sources, often spanning multiple locations, formats, and applications. All data is aggregated for analytical purposes. In this framework, sources include mobile applications, software programs, sensors, and web platforms.

F. Big Data Transformation

The data collected from various sources is initially raw and requires modification to fit suitable formats. Middleware can facilitate this by enabling the sharing of web services within a service-oriented architecture. In some instances, software applications may be necessary to extract, transform, and load (ETL) data for further processing. Data warehousing can also play a role in this transformation, as it aggregates data from multiple sources on a regular basis, preparing it for additional analysis. Different data formats can be created and utilized as input for big data analytical tools, depending on whether the data is structured, semi-structured, or unstructured [33].

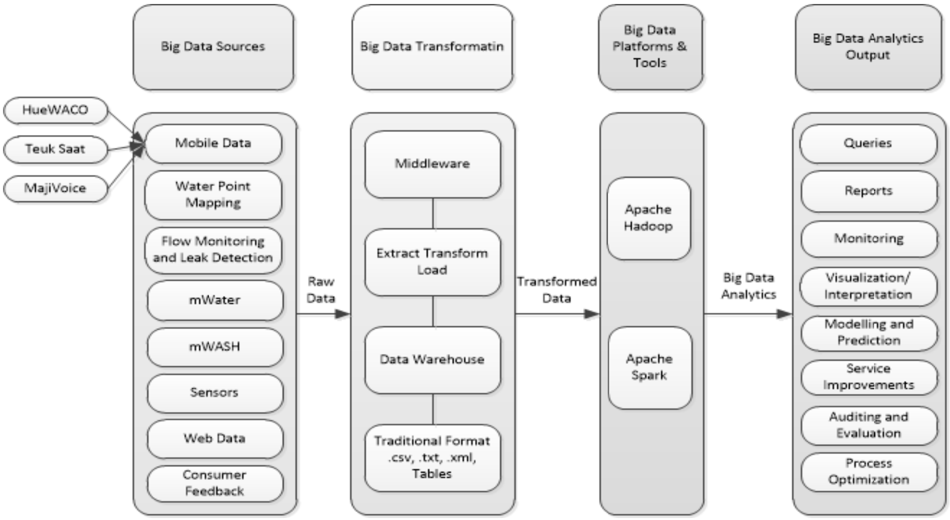

Fig. 8. An outline of Big Data Analytics in WASH sector

G. Analytics Tools for Big Data

Utilizing the transformed data, key decisions can be made through the application of analytical models and tools such as Apache Hadoop and Apache Spark.

4. Apache Hadoop

Apache Hadoop is an open-source software framework that enables parallel and distributed processing of large datasets across clusters using various programming models. A cluster can consist of anything from a single machine to thousands of computers, each equipped with its own storage and processing capabilities. Hadoop is designed to manage failures effectively and ensure high availability. It is commonly understood that Hadoop consists of two primary modules [34].

a. Hadoop Distributed File System

Hadoop includes a distributed file system known as HDFS, or Hadoop Distributed File System. HDFS is designed for storing very large files on clusters of standard hardware. "Very large" refers to files that can range from megabytes to terabytes or even petabytes in size. The system is based on the principle that the most effective data processing approach is to write data once and read it multiple times. Hadoop does not require expensive, highly reliable hardware; instead, it operates on clusters of commodity hardware, which may have a higher likelihood of node failure. However, HDFS is engineered to function seamlessly without significant interruptions for users, even in the event of such failures. Datasets are divided into smaller blocks, typically around 64 MB in size, which are distributed across the machines in the cluster via HDFS. With a moderate level of data replication, cluster machines can read datasets in parallel, resulting in significantly enhanced throughput.

b. Hadoop MapReduce

MapReduce programs operate in two primary stages: mapping and reducing [35]. Each stage is handled by specific functions known as mapper and reducer functions. Programmers write code for these functions within the framework. During the mapping phase, input data is provided to the mapper, which produces key/value pairs as output. This output represents intermediate records created from the input data. These intermediate records, formatted as key/value pairs, then serve as input for the reduce phase. In the reducing phase, the MapReduce framework groups all the intermediate values and generates the final desired output. Essentially, the mapper's role is to filter and transform the input data into a format that the reducer can efficiently aggregate.

5. Apache Spark

Apache Spark is a big data processing engine that operates on a cluster in a distributed manner. Applications run on the cluster as a set of independent processes. A central coordinator oversees all processes and can communicate with three different cluster managers. Spark employs a master/slave architecture, where the central coordinator, referred to as the driver program, is the primary process that executes the code using the SparkContext object. This driver process breaks a user application into smaller execution units known as tasks. Individual tasks are executed by executors, which are worker processes.

Within a cluster, there is one master node and multiple worker nodes. The driver program runs as an independent process on one of the workers, while the cluster manager supplies the necessary executors. The driver program is responsible for scheduling tasks on the executors, which are allocated by the cluster manager. The cluster manager is in charge of scheduling and distributing resources across the host machines that make up the cluster.

H. Findings of Big Data Analytics

The findings from big data analytics can be utilized to enhance the measurement and monitoring of interventions, foster relationships, empower local practitioners, and inform decision-making aimed at the sustainable and equitable expansion of water, sanitation, and hygiene (WASH) services. Through big data analytics, reports and queries are produced that aid in the decision-making process. The insights gained from big data analysis contribute to enhancing WASH facilities by implementing specific initiatives within communities and providing support to governmental efforts.

1. Social Accountability

Big data analytics helps to store, process and manage huge amount of real time data to enhance transparency and accountability of e-governance in the WASH sector so that it engages citizens and communities for the formation of government, ensuring that decisions made by individuals and organizations are transparent to the public. It aids in planning and development, budget setting, expenditure tracking, and project performance monitoring. Additionally, it fosters accountability among community members and organizational staff in adhering to local agreements.

2. E-Governance

A significant challenge faced by governments in this sector is the lack of information. Donor governments are often unaware of the spending status and planned expenditures of other donors. Similarly, recipient governments may not have insight into how much of the budget has been allocated and spent in their own countries. This lack of transparency complicates budget planning and undermines accountability, as citizens remain uninformed about the funds allocated by the government for their benefit. Civil society, however, has the right to know both the amounts received in the country and how much has been spent.

3. Open data and accountability

In the water sector, financing is sometimes opaque, and reporting practices tend to rely on paper-based methods, which are ineffective. There is often a lack of clarity regarding how funds are allocated and where they should be applied. These issues can be addressed through the use of technology, enabling governments to access and utilize data more effectively. It is essential to ensure that collected funds are invested in initiatives that will benefit society and the nation in the long run.

Successful societies often develop their infrastructure through technological advancements. For countries to thrive, they should embrace open content, open data, and open-source software. Open data is crucial because it promotes efficiency, reduces costs, enhances democracy, ensures sustainability, and fosters innovation.

4. Post Implementation Monitoring (PIM) Surveys

The challenge of conducting post-implementation monitoring surveys is crucial to ensuring that access to water supply and sanitation services provided by the WASH sector remains effective even after a project concludes. Comprehensive monitoring of the WASH services that have been implemented is vital for the long-term operation, maintenance, repair, and expansion of these systems. Post-Implementation Monitoring (PIM) helps enhance the understanding of how the installed water supply and sanitation systems are utilized and their overall functionality after they have been handed over by the use of big data analytical tools such as Apache Hadoop and Spark.

5. Using data for equity and sustainability

While large volumes of data can be gathered, the challenge lies in utilizing it effectively. Leveraging data for decision-making is crucial for enhancing the quality and sustainability of WASH services. Data provides insights into the real conditions on the ground. When results are available, it enables the efficient allocation of resources toward WASH services, as data supports evidence-based decision-making for the expansion of service delivery. Ultimately, data aids in making informed decisions, expanding WASH services, and achieving tangible results through the effective utilization of resources.

6. Visualization

Analytics heavily relies on the ability to produce meaningful outputs. Various tools and technologies like sensors and IOT devices, Remote sensing and Geospatial technologies, data integration platforms, social and behavioral data collection, WASH infrastructural monitoring, Environmental monitoring tools have been developed to collect, and big data analytics helps to process, and display the result in visual form for the decision makers. Big data analytics also takes support of other disciplines such as statistics, economics, applied mathematics, and computer science for the analysis of the results.

7. Monitoring

Monitoring can be enhanced to facilitate government-focused analysis, utilization, and updating of water infrastructure data. By analyzing maps generated from collected data, it becomes possible to identify areas that require investment. For instance, this process can involve categorizing regions with the highest needs or pinpointing the main causes of water point failures. Decision-makers can then allocate funds for the upcoming year based on the identified needs of these water points.

8. Scalability and Cost Consideration

Scalability and cost considerations for big data analytics in the WASH sector are crucial for ensuring the effectiveness and sustainability. As data are increasingly rapidly, infrastructure requirements are also needed in the same way. Big data analytics helps the WASH sector to process such a huge amount of data as per requirements of hardware and software and with the minimal requirements of resources, it can process terabytes of data in real time. It is also cost effective because it reduces operational cost and uses open source solutions and has provides sustainability and maintenance.

Conclusions

The article concludes by underscoring the transformative role of big data and information communication technologies (ICT) in addressing critical global challenges across multiple sectors, with a particular focus on the Water, Sanitation, and Hygiene (WASH) sector. Through advanced data collection, analytics, and visualization tools like Apache Hadoop and Spark, big data enables organizations to gain meaningful insights, enhance efficiency, and support data-driven decision-making. The findings highlight how big data analytics improves resource management, supports transparency, and promotes sustainable development by fostering social accountability, open data, and equity. Ultimately, the article emphasizes that effective use of big data analytics is essential for developing innovative solutions that address societal needs, improve governance, and ensure equitable and sustainable access to vital resources.

Future enhancements to this article could include an in-depth exploration of emerging technologies such as artificial intelligence (AI) and machine learning (ML) in big data analytics, especially how these technologies can further improve decision-making in the Water, Sanitation, and Hygiene (WASH) sector. Adding case studies on real-world implementations of big data in underdeveloped regions could provide valuable insights into its challenges and successes in various socio-economic contexts. Additionally, the article could expand on ethical considerations, including data privacy, security, and responsible data usage, especially given the sensitive nature of data in public health and environmental sectors. Further, it would benefit from discussing the potential for integrating big data analytics with predictive modeling and simulation tools to anticipate future needs and risks in WASH and other sectors.

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