Cloud Computing in Natural Hazard Modeling Systems: Current Research Trends and Future Directions[1]

Abstract

Every year, natural disasters cause major loss of human life, damage to infrastructure and significant economic impact on the areas involved. Geospatial Scientists aim to help in mitigating or managing such hazards by computational modeling of these complex events, while Information Communication Technology (ICT) supports the execution of various models addressing different aspects of disaster management. The execution of natural hazard models using traditional ICT foundations is not possible in a timely manner due to the complex nature of the models, the need for large-scale computational resources as well as intensive data and concurrent-access requirements. Cloud Computing can address these challenges with near-unlimited capacity for computation, storage and networking, and the ability to offer natural hazard modeling systems as end services has now become more realistic than ever. However, researchers face several challenges in adopting and utilizing Cloud Computing technologies in this area. Moreover, accessing the Cloud services during the disaster where the communication and power supply can break down, is still an open challenge. As such, this survey paper discusses these challenges, needs and existing problems to reflect the current research trends and outlines a conceptual Cloud-based solution framework for more effective natural hazards modeling and management systems using Cloud infrastructure in conjunction with other technologies such as Internet of Things(IoT) networks, fog and edge computing. We draw a clear picture of the current research state in the area and suggest further research directions for future systems.

Keywords:
Natural Hazard, Disaster Management, Geospatial Science, Cloud Computing

[1]Declaration of interests: none

1. Introduction

According to the record of Emergency Events Database, natural hazards have cost about 3 trillion dollars of economic destruction and 1.3 million casualties with more than 4.4 billion people injured between 1998 and 2017[1]. Despite the development of various technology aided systems to understand and mitigate the effects of natural hazards, effective disaster prediction and management continues to be a worldwide issue. Various time windows can be categorized for Natural Hazard Management. A wide range of activities can be carried as a pre-planning step to mitigate the dangerous impacts of a potential hazard. Such preparedness before the occurrence of a disaster, as well as rapid damage assessment after a disaster, can be hugely important in ensuring the least damage is inflicted in terms of lives and infrastructure. Activities carried out during a disaster, such as faster and real-time modeling, allow effective operational strategies to be developed and implemented to decrease the impacts of the disasters.

A wide range of models have been constructed for predicting natural hazards and effective disaster management. These include wildfire propagation models (Spark[2], Phoenix[3], FARSITE[4], Prometheus[5]), flood spread models (Swift[6], Rapid Flood Spreading Model (RFSM)[7]), dust storm forecasting model[8], landslide prediction model (Landslide Hazard Assessment for Situational Awareness (LHASA) model[9]), cyclone models (Hurricane Weather Research and Forecasting (HWRF) model[10], Beta and advection (BAMM) model[11]), earthquake models (KanaiTajimi model[12], Dilatancy-diffusion model[13]) and many others. On the other hand, many studies have investigated and integrated various aspects of ICT in Geospatial Science and Disaster Management so as to work efficiently for the prevention and management of natural hazards. Satellite Remote Sensing, along with various monitoring and alerting tools, had been effectively used to study and manage the natural disasters. The recent advancements in technological aspects have made Geospatial Science face multiple challenges related to computation, storage and network. Geospatial Science collects, stores, analyzes, processes and simulates data from different regions of the world. The workload and scope of this have exponentially increased with the development of new sensors, the sophisticated information collecting methods and further understanding of Geospatial processes. This proceeding has made

Geospatial applications and services data-intensive, compute-intensive and concurrent access-intensive. Hugely massive data sets collected from large regions in multi-temporal and spectral dimension, by using high-end resolution sophisticated sensors, have contributed to a huge bottleneck of data in Geospatial Sciences[14]. The algorithms and models developed in Geospatial Sciences are becoming more complex with an improved understanding of spatio-temporal principles driving those phenomena[15]. These models may require ensembles of simulations for better disaster risk metrics, which is computationally intensive to implement. The recent rise in popularity of web and wireless devices has made it possible for numerous end users to access the services concurrently. These models, when offered as end services, invite various challenges of having to keep up with as fast as possible access and respond to sudden change in the number of concurrent users[16].

The implementation of Geospatial and natural hazard models over the traditional ICT foundation has become non-trivial and the researchers have turned their attention to Cloud Computing. Evolved from the principles of distributed computing, Cloud Computing possesses the ability of pooling, sharing, integrating the latest computing technologies and physically distributed computer resources [17]. Cloud Computing provides an on-demand and elastic access to an almost unlimited storage, network and computational resources. These features directly address the challenges of data, compute and concurrent-access intensiveness in the implementation of Geospatial models for disaster management. The adaptation of Cloud Computing in Geospatial Science for Natural Disaster Management(NDM) is one of the least explored areas despite the fact that Cloud Computing has a tremendous potential to revolutionize the disaster management with its neat shared architecture of infinite storage and computing resources.

There are a few research areas where Cloud Computing has been used in Geospatial applications for NDM to enhance the performance of the system with reduced cost and complexities. The exemplars presented by Yang et al.[18] provide a brief insight into how Cloud capabilities were used to support specific requirements of different applications. The work done so far has been able to initiate and verify the suitability of the use of Cloud Computing in Geospatial Science for NDM. The ability to offer the functionalities of NDM as end services is attractive to researchers and is now relatively easier to achieve. However, a neat and effective approach is yet to be determined to enable this so as to replicate the success of Cloud environment achieved in general computing, in NDM. Moreover, due to huge dependency of Cloud

Computing on internet connectivity and regular power supply, the use of Cloud services can be difficult during the actual occurrences of the disasters when the communication and electricity infrastructure may break down. Cloud Computing offers better solution for disaster modeling and simulation but easy and efficient access to Cloud infrastructure, specially during the disaster, is still one of the key challenges.

A wide range of work to integrate Cloud Computing technologies with disaster management is found across the research domain. A comprehensive reflection of current research trends to highlight the existing research gaps, needs and problems is required in this research area. This clear picture of the research trends is expected to lay a strong foundation for well-directed future works for more effective NDM to ensure minimal losses inflicted by natural hazards to the global community. There are some attempts made to highlight the current research trends in adaptation of ICT in NDM. Yang et al.[15] explained how Cloud Computing could shape the future of Geospatial Science for advanced functionalities and capabilities taking four works as use cases in their work. Hristidis et al.[19] presented a comprehensive survey of data management and analysis in disaster situations to present the current state of knowledge, challenges and future research directions. A survey along with five papers are presented by Yang et al.[18] showing how Cloud technologies were capable of addressing the issues of Geospatial Science. None of the studies done so far have summarized the work done to integrate evolving Cloud technologies to support various aspects of disaster management, giving a clear picture of the current research state. As such, this proposed study aims to fill this gap by presenting a synthesized and comprehensive summary of relevant works to reflect the current research trends and future research directions. The contributions of this work are listed below:

1. Highlights the key challenges in the extensive use of Geospatial models for NDM over the existing computing infrastructure
2. Proposes a conceptual Cloud-based solution approach for facilitating an easier integration of Cloud technologies, together with other technologies such as IoT networks, fog and edge computing, in Geospatial Science for offering NDM as end services
3. Reflects the current research trends through a comprehensive summary of relevant works done in utilizing ICT infrastructures including Cloud Computing to support different aspects of NDM.
4. Highlights and analyzes the existing research gap in Geospatial Science

in regard to offering NDM as a Service and presents well-defined future research directions to fill the gap for the advanced capabilities in the discipline.

This paper is organized as follow: Section 2 explains the basic concepts of various aspects related to the use of Cloud Computing in Geospatial Science for NDM. Section 3 describes a proposed Cloud-based solution to accommodate the complex Geospatial models over the Cloud infrastructure. Section 4 reflects the current research trend under different categories while Section 5 analyzes the existing research gap and discusses the further research directions. Section 6 concludes the paper.

2. Background

This section briefly explains the basic concepts of Disaster Management, Geospatial Science and Natural hazards, use of ICT tools in NDM, Cloud Computing, and use of Cloud Computing in Geospatial Science for NDM.

2.1. Natural Disaster Management and Its Aspects

Natural disasters, whether caused by natural or human-induced factors, cause large-scale destruction of the environment and physical infrastructure and directly threaten lives. It is a difficult task for authorities to formulate and implement effective strategies to minimize the dangerous impacts of the disasters. There is a wide range of activities that can be specifically directed and carried out at different stages of a natural disaster but an effective management of these activities, commonly referred to as *Natural Disaster Management(NDM*, is required to ensure least damages are inflicted by the disaster. The comprehensive approach[20] has been widely used in NDM. This approach comprises of four phases namely - prevention, preparedness, response and recovery and is commonly referred to as PPRR framework for disaster management. Figure 1 show the four phases in PPRR framework which are not linear and independent as they overlap and support each other for a better balance between risk reduction and community resilience for better response and effective recovery.

2.1.1. Prevention

The risks of some natural disasters can actually be reduced or eliminated by carrying out proactive and counter-effective measures before the occurrence of the disasters. The possibility of prevention of the disasters is based

Figure 1: Comprehensive Approach to NDM[20]

on the factors contributing to the outburst of the disaster. The occurrence of flooding events can be prevented by erecting and reinforcing dams around the rivers or finding an alternate way out for the water in case of increased water level as suggested in the work[21]. For the disasters whose occurrences can be prevented, necessary actions can be taken after analyzing relevant information so as not to concede any loss to the disasters.

2.1.2. Preparedness

For disasters which cannot be mitigated, responses can be prepared by analyzing current information on the disaster to reduce potential impacts. For example, faster than real time models of disaster outbreak can predict which areas will be impacted as done by Cohen et al. using Swift[6] for urban flood prediction and Miller et al. using Spark[2] for wildfires. Evacuation strategies can subsequently be developed accordingly. For earthquakes, preparatory actions could include managing open spaces for communities and forming effective strategies for deployment of earthquake-response units as highlighted by Allan and Bryant[22]. Co-ordinated action and plans as emphasized in [20] are necessary for an effective preparedness against any natural disaster.

2.1.3. Response

Response and resource mobilization during a disaster is critical in saving human lives and reducing physical losses. Authorities can acquire, collect and analyze real-time information about the disaster to form effective strategies for effective response. For example, search and rescue operations carried out during a disaster can be improved by making effective use of technical tools, like monitoring tools and communication methods as studied by Fiedrich et al. in [23] against earthquakes.

2.1.4. Recovery

It can be very complicated and protracted to recover and return to normal life once the disaster has inflicted damages to the community. The recovery efforts should align with the need of the area affected by the disaster for best outcomes. Post-disaster, the damage in terms of lives and economic value must be assessed using appropriate cost assessment methods for better reconstruction phase after the disaster as summarized in [24]. Authorities employ various methods for collating data from the event which is used for the prioritization of infrastructure repair as in [25] and to guide future management strategies and plans.

2.2. Geospatial Science and Natural Hazards Models

Geospatial Science, also referred to as Earth Science, is the study of various physical constitution and components of the planet and its atmosphere. Geospatial Science comprises the studies of the earth's physical characteristics ranging from the raindrops to fossils including earthquakes and floods. The scope of Geospatial Science can be huge, with complex interactions between different components. To study and understand these complex phenomena that occur around the planet, Geospatial Science uses different models that provide a picture of the past, present and future of the natural systems and processes.

Modeling is crucial in Geospatial Science as it helps the researchers to simulate the complex physical processes of earth systems [26]. For example, climate models simulate the future climatic conditions and changes for years to come simply by simulating the interactions among different factors such as atmosphere, land surfaces, biosphere, ice, and oceans using the past climatic condition records [27]. The same approach of modeling is used to study the phenomena of natural hazards to predict their outbursts. For example, a model can be constructed for predicting the spread of a wildfire in a particular region by studying and simulating the complex interactions with several factors including vegetation, climatic conditions, fuel models, altitudes, chemical reactions and turbulent interactions with the atmosphere.

The implementation of simulations in Geospatial models possesses a number of challenges. The highly complicated nature, compute-intensive nature, specific time requirements, need for scalability for ensembles of simulations and data-intensive nature of Geospatial models are what make the implementation a complex process[15]. The complex interaction between all the influencing factors to the natural phenomenon makes the task of setting up a Geospatial model intensive with respect to computation and data. Most of the models require the complex simulation to be repeated a number of times for different points in the region being considered. The natural models for weather, hazards and dust predictions should run and complete within a specific time requirement as these predictions are time-sensitive and could make delayed predictions obsolete. These Geospatial models usually employ an ensemble of numerous simulations for more accurate risk metrics. These specific runs require scalable computing resources which can adapt to the ever-changing requirements of the models. Moreover, given the recent advancements in the data collection techniques and number of inputs, a model could be dealing with a huge volume of data even for the little duration of time[14]. For example, the weather prediction model could be generating terabytes of data just for few days of prediction thereby making the data handling a challenging task in Geospatial models.

2.3. ICT In Natural Disaster Management

There are different aspects of natural disasters where effective management is required before, during and after the occurrence of the disaster. Depending upon the phase of the disaster, a wide range of ICT tools can be used for different activities so as to minimize the impacts of the disasters. The foremost step in the disaster management is to collect the relevant statistical data related with the particular disaster and correctly analyze and identify the risks and dangers associated with the disaster[20]. The next step is to look out for the measures that can be taken in order to prevent, mitigate and prepare for the emergencies caused by the disasters.

The use of ICT technologies can significantly improve the management of the disaster by performing different activities in efficient and convenient ways[28].The use of Geographic Information System (GIS) allows the potential risks and dangers of a disaster can be identified and the geographical areas to be classified into different level of vulnerabilities for effective mitigation planning. The technological foundation of ICT can also be helpful in early warning systems which can help authorities and people save lives. The use of ICT tools can be crucial in the collection of information from multiple system and sources during the occurrence of the disasters and forming operational plans during the emergency. The transfer of critical information during the emergency can be implemented using various ICT tools for effective mobilization of resources. Along with the Remote Sensing and satellite data, ICT can contribute through visualization of real-time information after the disaster has struck. Moreover, the foundation of ICT can allow the execution of different simulations to predict the nature and spread of different natural hazards and make necessary arrangements and preparations accordingly to minimize the impacts of the disaster.

The use of web, web-based applications, communication tools and visualization platforms are pivotal in providing useful information about the disasters [29]. However, the evolution of different Geospatial models for different natural disasters and parallel development of sophisticated data collection methods, the conventional methods of using ICT for disaster management have become outdated. The challenges of data-intensiveness, compute-intensiveness and concurrent access-intensiveness have been added to the disaster management making it a hugely complex task to handle. Cloud Computing has emerged as an attractive alternative to address the new challenges in the field of disaster management.

2.4. Cloud Computing

Given the need for elastic on-demand resources for parallel and distributed computation in various application, Cloud Computing has emerged as a new technology that exploits the principle of distributed computing in multiple virtual machines. The National Institute of Standards and Technology (NIST) has defined Cloud Computing as "*a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction*[30]".

The introduction of Cloud Computing has revolutionized the way computation is carried out in organizations and research. Computation is now considered as a utility service, rather than the traditional model of owning and utilizing resources for different application. This shift of computing paradigm facilitates the users to focus more on their application and spend lesser time on repairing and maintaining the resources. Irrespective of the ways Cloud Computing is defined, there are some inherent features which Cloud Computing is expected to possess. Cloud Computing provides an almost unlimited capacity for computation, storage and networking through its vast chain of virtualized resources ensuring key features of on-demand service. These include ubiquitous network access, independent resource pooling, rapid elasticity and a service-based approach. The concepts of different Cloud service models and deployment methods are summarized in Figure 2 to show how the Cloud environment can be used under different configurations.

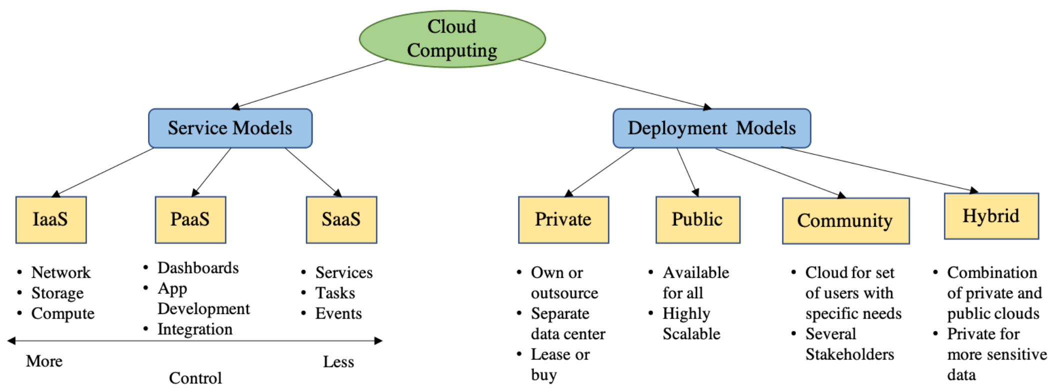

Figure 2: Cloud Computing: Service and Deployment Models

2.4.1. Cloud Service Model

Cloud Computing facilitates the consumption of Cloud services and utilities at different levels. As such, Cloud Computing has been classified into three distinct categories based on the services and abstraction levels at which it offers the advantages to its users. The three categories of service models are explained below:

Infrastructure as a Service (IaaS). IaaS stands on the lowermost layer of a managed Cloud service ecosystem providing virtualized and pre-configured hardware services. It provides the services of networking, servers, virtualization components and storage and the users have to take care of all other aspects of hardware including the installation and maintenance of the operating system, applications, databases and security components. Amazon Elastic Compute Cloud (EC2) is a good example of IaaS.

Platform as a Service (PaaS). PaaS manages all the hardware-oriented functionalities such as operating system installation and updates and security patches maintenance and provides a versatile foundation for developers to develop, test and deploy applications with a wide range of functionalities. It includes various APIs and tools to facilitate monitoring of services, version control of systems and work division. Microsoft Azure and Google Cloud Platform are well known PaaS solutions.

Software as a Service (SaaS). SaaS is a service offered to end users through a web-based interface over the internet where the users have the least flexibility in terms of the environment and hardware over which the services are running. The users do not have to worry about development, update, backup, support or maintenance of the services as the service provider takes care of everything. Gmail, Dropbox, and Netflix are popular existing SaaS services.

2.4.2. Cloud Deployment Model

There are different ways how the Cloud services are deployed to offer various services to its users.

Private Clouds. In a private Cloud, a business firm is the only entity that has access to the Cloud services as the Cloud services are not shared with anyone else. The firm deploys its own applications and services that are accessed by the personnel inside the company through intranet over secured connections. The payment system is often a fee-per-unit-time based scheme.

Public Clouds. In a public Cloud, the business firms access the Cloud services provided by a Cloud service provider and hence, multiple business firms can access the same Cloud infrastructure based on the subscription schemes. The Cloud service provider maintains the security in the Cloud services to deny any unauthorized access to the services. The payment scheme is usually a pay-as-you-go model based scheme.

Community Clouds. In community Clouds, specific business communities can have access to a complete Cloud solution provided by a Cloud service provider. The Cloud infrastructure are shared by the business firms but they have their own private Cloud space so as to meet the common privacy, security and compliance needs of the community. This model can be helpful in providing the complete Cloud solutions to business entities with a common interest to meet their specific needs.

Table 1: Pros and Cons of Cloud Computing

Pros	**Cons**
- Near-infinite capacity of compute, storage and network	-Latency related Issues
- Reduced Capital Expenses	-Security Issues
- Ubiquitous Access	-Compliance and Regulatory Issues
- Redundant Data Storage	-Interoperability Issues
- Scalable resources	
- Flexibility and Mobility	
-Reliable services	

Hybrid Clouds. In hybrid Clouds, the Cloud deployment lies between public and private where sensitive and critical data are stored in private Cloud for the highest level of security while other operations are carried out in public Clouds. Hybrid Clouds can help business to reduce the costs by providing the option of running all their services over the public Clouds without comprising their sensitive data.

2.5. Pros and Cons of Cloud Computing

With its vast network of physically distributed data centers, Cloud Computing has advantages of reduced capital costs, robust and redundant data storage, ubiquitous access and on-demand and scalable resources[31]. But, Cloud Computing is hugely dependent on the internet connectivity and the power supply that operates the data centers. Because of the remote location of the Cloud servers, there may be latency and bandwidth related issues[32]. In addition, there may be issues related to security, compliance and regulation[32]. Because of multiple Cloud platforms, developing services may have interoperability issues. Despite these cons, Cloud Computing offers a more robust, reliable, scalable and cost efficient solution compared to local computers and small cluster of computers. Especially for the disaster management, because of its features, Cloud Computing stands as an indispensable entity, which can be used in conjunction with other evolving technologies for the most effective use. The pros and cons of Cloud Computing are summarized in Table 1.

2.6. Cloud Computing in Geospatial Science for Natural Disaster Management

The challenges of the compute, data and concurrent-access-intensive nature of Disaster Management models as end services make traditional computing infrastructures less fit for purpose than Cloud Computing. The additional needs of scalability, dynamic reconfiguration, easy access, and distributed operation of the models have also make a Cloud Computing foundation an attractive choice as Cloud technologies have the potential to provide support for all those needs. Given the rise of Cloud Computing infrastructures for the deployment of various services and applications, researchers have been looking to Cloud Computing to address the challenges and issues associated with Geospatial Science for Disaster Management. Cloud Computing provides new capabilities to Geospatial Science with its almost unlimited capacity of computation, storage, and networking resources to handle the associated challenges.

Geospatial Science encompasses sectors such as energy and mineral science, climate science, ecology, environmental health, water management, disaster management and traffic management. Cloud Computing has had limited success in these areas due to the low levels of current integration between Cloud Computing and Geospatial Science. Li et al.[33] used features of Cloud Computing to address the complex demands of data, storage, and processing for energy information management. The challenges of large-scale data management, analysis and processing of climate Science were handled using Cloud Computing by the introduction of community defined services such as Earth System Grid [34]. The need of real-time capabilities to solve data-intensive problems and offer on-demand services to a dynamic number of end users in traffic management and surveillance was addressed by Li et al.[35] by using Cloud Computing. The inherent challenges of ecology in regard to storage, scalability, platform integration and deployment were addressed by the use of Cloud Computing in conjunction with Geospatial Science[36]. The Cloud Computing also facilitated the support for ensemble runs for predicting and forecasting the availability of freshwater and spread of different natural hazards[37]. The needs for flexibility and extensibility in visualization, monitoring, warning, preparing and responding to fire disasters were also met with the introduction of Cloud Computing[38].

The work carried out so far has illustrated how the use of Cloud Computing technologies has brought in various advanced capabilities in the implementation of models in Geospatial Science for NDM. Further work can be developed on this foundation to offer functionalities of NDM as services to close the gap between these Geospatial models and their users.

2.7. Challenges in Implementation of Disaster Models as Services

Natural hazard models developed using Geospatial principles can be contribute to understanding the complex nature of natural disasters and reducing their impacts. However, the ability to easily and conveniently use these models as end services are prevented by a number of challenges which are described below:

2.7.1. Compute-Intensive Nature

The models and algorithms are generally very complex as they are based on physical models with additional relationships between various model components. The development of new technologies has contributed to better understanding the phenomenon[15] but has increased the implementation complexity due to the large datasets produced. The computational power required to support these models has also drastically increased and consequently, traditional sequential computing techniques and single machine are not able to keep up with the increased computation demands. Natural Hazard models now require a high-performance computing scheme to be able to meet the increased computation demands, which is not possible for every organization wishing to use such models.

2.7.2. Data-Intensive Nature

The scale of recent advancements in data sensing technologies means that Geospatial Science must now handle massive data sets. Cui et al.[14] highlighted the support of massive data as one of the long-term bottlenecks in Geospatial Science due to the amount of data accumulated by in situ sensors and satellites. Satellites currently collect petabytes of Geospatial data annually(more than 4 petabytes in 2019)[39]. Moreover, the scattered nature of data, non-uniform formats, diverse temporal scale of incoming data and service types of Geospatial models result in significant challenges in the organization, administration and processing of the data.

2.7.3. Concurrent-Access-Intensive Nature

The rise and success of web and wireless devices has enabled a large mass of end users to access Disaster Management services concurrently from a diverse range of geographical locations[40]. These web-based services must offer customized services to end users based on user requirements and sets of user inputs. Additionally, these services must have the ability to provide fast access and respond to sudden change in the number of concurrent accesses to the services. The number of users of a disaster model service can peak during the event of occurrence of the disaster while the number of the users may be low during other time. The ability to respond to these access spikes is a key requirement for a disaster management service[16]. Effective management of the resources must be realized for optimized and uncompromised user experience while facilitating concurrent access to the services.

2.7.4. Time-Critical Requirements

Based on the complexity and level of interactions between different factors for particular natural disasters, the implementation of Geospatial models and processing can be time-consuming. Specially, for predictions from natural disaster models the time taken for producing the results and relevant alerts are highly critical to operational management. During the occurrence of natural disasters, any prediction results obtained quickly about the spread of the disaster could be crucial in saving and preventing further damage and loss. Given the complex natures of the models in Geospatial Science, it is a challenging task to handle the resources so as to be able to meet the strict time-critical requirements of the models and services.

2.7.5. Inaccessibility of Cloud Infrastructure during Disasters

Cloud Computing is hugely dependent on the internet connectivity and the regular power supplies that keep the data centers running. Depending upon different forms of the disasters, the infrastructure for communication and electricity can be significantly damaged. The communication infrastructure was non-functional for a prolonged time due to an earthquake in 2011 in Japan[41]. Similarly, the regular power supply was reported to be interrupted frequently because of different natural disasters such as hurricane, earthquakes and so on[42]. In such disaster circumstances, despite the fact that Cloud Computing offers attractive solution for disaster modeling and simulations, Cloud services cannot be easily accessed. As such, determining the effective ways to either make Cloud services accessible through other alternate methods or integrate other related technologies for better response during the disasters, is still an open challenge.

3. Proposed Cloud-based Conceptual Solution

This section proposes a conceptual Cloud-based solution for easier integration of Cloud Computing technologies with Geospatial Science for delivering NDM capabilities. The proposed solution aims to expose the capabilities of Cloud Computing to complex disaster management models in order to address the challenges associated with offering Disaster Management as end services. There are three major blocks in the proposed concept that handle different tasks independently focusing on specific aspects of the entire system. The User-interface is the one and only point of contact between the users and the Cloud-based system in which users can initiate requests and get a desired output after suitable processing and execution. The Cloud Infrastructure block provides all the hardware capabilities (compute, storage and networking) required for the execution of any processes and simulations as initiated by the users. The Control Mechanism block is central to the proposed solution as it governs all the mechanism for handling and managing the user requests and Cloud infrastructure to produce the desired output in an optimized manner. The block of other related technologies such as IoT network, fog and edge computing, is an extension under the umbrella of Cloud computing that offers some time-critical and less compute and data-intensive disaster-related services and acts as a transitional data ingestion point during the disaster due to the realistic fact that the Cloud services may not be accessible because of communication and power supply breakdown during the disasters. The composition of the proposed solution is shown in Figure 3 while the desirable features of each block are summarized in Figure 4. Each components and how the proposed Cloud-based solution can be used effectively, are described below.

3.1. Component Overview

3.1.1. User Interface

The first block in the proposed conceptual solution is a user interface block that offers an interface to different end services as facilitated in the entire system. This is the front-end of the Cloud Computing based system and accessible to the users through the use of web services and different application program interfaces (APIs). The user interface block is critical to the system as the block encapsulates the entire operation of the system and is the single point of interaction between users and the system. The block should facilitate the initiation of the user request and collection of the results. The user should be able to use the functionalities of the entire system and

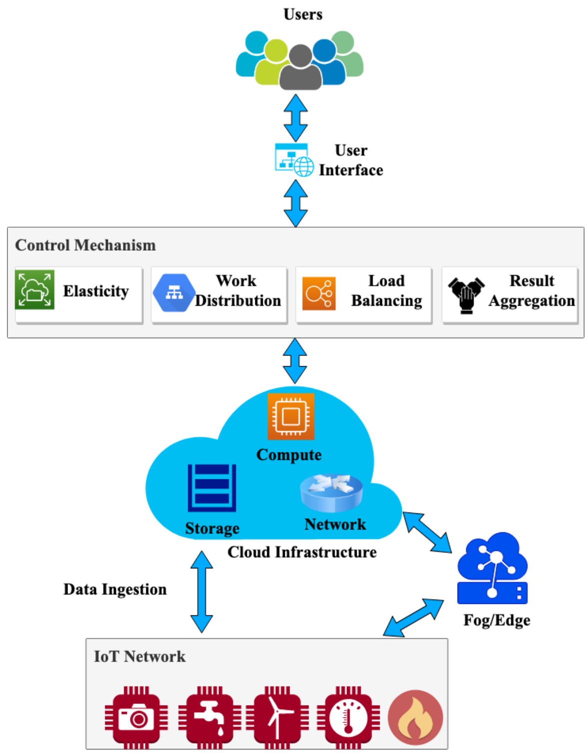

Figure 3: Proposed Cloud-based Conceptual Solution

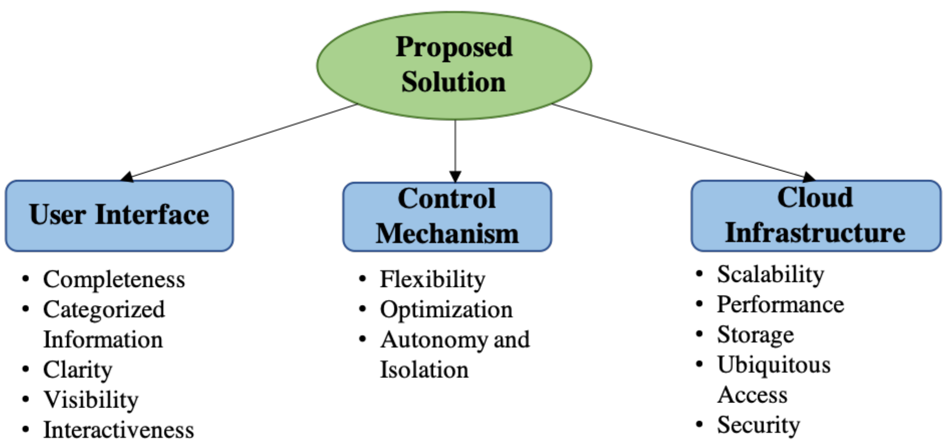

Figure 4: Desired Features for the blocks in Proposed Solution

execute models through this block, including entering input parameters and displaying results obtained from the models.

Desirable Features.

- Completeness. For a system implementation of NDM models, the user interface acts as the single point of the control for the users and the system that runs the required operation to produce relevant sets of outputs. It is therefore critical that the block remains complete at any instant. The block should be able to provide complete information to the system and users. The block should ensure the system can acquire the complete set of input parameters for running models in the system. This also holds whenever the block is interpreting the results obtained from the system to users and the interface block should be able to provide complete information about results obtained after complex runs of the model. It is desirable that all the information held over the block before, during and after the run of the models is complete.

- Categorized Information. The users of NDM models can comprise a diverse range of people with varying level of knowledge about the related phenomena. When offered as end services to these users, the user interface should be able to represent the relevant information that is useful and understandable to any categories of users. The dispense of information related to any Geospatial process or any disaster should be managed under different categories and reflected in the user interface with proper isolation for any confidential or sensitive information through proper security measures. Users should be able to derive and understand the important and desired information from the system through the use of user interface irrespective of the role they play during the disasters or any earth processes.

- Clarity. Depending upon the processes of various Natural Hazards, the system may take up a range of inputs to produce a large set of outputs. The types of operation that are carried out to produce the desired outputs can also significantly vary. From a user perspective, the interface is the only point of contact with the system and hence the interface should try to maintain a clear line between different aspects of the model. There must be a clear picture of input parameters and how they are likely to govern the operation of the entire system. The user interface of the system should have a distinct line of clarity to dispense any information related to the status of the system or results obtained from the model run so as to make them easily understandable and readable.

- Visibility. Given the compute-complexities of the Natural Hazard models, the system may not be able to produce the desired results instantaneously and the users might have to endure significant waiting time. As the user interface block is the sole representative of the entire system architecture, it is desirable that the block represents the operational states of the system at different instances of time. Along with the user inputs and the results obtained after the run of the model, the user block should ensure visibility of the system status to facilitate easier display and interpretation of any information related to the system to improve the quality the user experience.

- Interactiveness. The models for NDM comprise of a large set of parameters and input data sets that are considered during the construction and implementation of a particular scenario. The ways in which inputs are entered into the system and how the results are displayed over the user interface are important as users of these services may have customized steps and visualisations of the results. Given the crucial nature of the user interface block in the conceptual solution, it is important to create and maintain an interactive experience for the users of the service. The block should add some elements of interactiveness while accepting inputs from users and interpreting the results obtained from models. The system should have a wide range of interactive options for displaying the results. The block could add options to toggle between various visualization options for the users to interpret the results from different perspectives and display any required useful information.

3.1.2. Control Mechanism

This block is the central component of the proposed solution as it employs various methods to prepare the existing Cloud infrastructure for complex NDM models. The different aspects of Disaster Management need to be managed effectively using relevant control methods so as to implement the models in a distributed fashion over the Cloud environment. Moreover, to effectively deal with the complexities related to the implementation of the models, there have to be different mechanisms for handling different aspects of the system independently. This block is basically a compilation of different functionalities that enables the smooth run of various operations in the system. The wide range of methods ranging from achieving the distributed mode of operations to optimization of the performance in terms of cost, time and resources is defined in this block.

Functionalities.

- Elasticity. The access of the service models offered with different functionalities of Disaster Management models can vary significantly based on the time within a year. For example, access to services related to bushfire would see a spike in the access and usage over the fire season and lower usage during other seasons. For flood, the maximum scale of access and usage of the services will be during rainy periods of the year with lower access and usage during other periods. As such, there should be an effective mechanism to handle this irregular pattern of usage and access so as to ensure better usage of the resources within the system. During a spike in user access, the mechanism should be able to add more resources in the system pool to provide an uncompromising system performance to the users and during the minimal usage, the mechanism should scale down and cut down on the resources to eliminate wasted resources.

- Work Distribution. The end services of delivering the functionalities of a Disaster Management System are complex as they comprise of a wide range of aspects related to the natural disasters and related processes. The system must not only handle multiple tasks at any given instant of time, but also take into account the diverse nature of the tasks. The tasks can vary from visualization to complex ensemble runs and handling the wide range of particular tasks types can be a complex process. A mechanism must be defined as to how multiple tasks of similar natures are to be grouped, where tasks of particular nature are to be carried out in the particular computing section of the system and how multiple tasks with diverse natures can be divided to ensure minimal cost. There should be an effective and efficient control mechanism for dividing the work obtained at any instant of time in the system to different nodes in the Cloud infrastructure in such a way that the desired outputs are obtained with optimized use of resources and minimum cost and time.

- Aggregation of Results. Geospatial processing can employ ensemble run of simulations with inputs values drawn from statistical distributions. These ensemble runs assign different jobs to a large number of computing nodes. Outputs from each of the processing nodes are crucial for the accurate presentation of the result. There must be an effective mechanism to keep track of the order of the outputs generated by each computing nodes as the jobs during the operations can be distributed in highly parallel fashion. Intermediate results may have to be stored for a final reduction step at the end stage of the ensemble run. An effective control mechanism must be integrated into the system to handle the large sets of output files generated during the operation and subsequent post-processing.

- Load-Balancing. The ensemble runs of Geospatial models employ a number of computing nodes for a single operation. Outputs from each of the processing nodes are crucial for the accurate delivery of the final result. Whenever a fixed number of computing nodes are assigned to a number of ensemble runs, there may be instances where one of the nodes completes the jobs early while the other takes more time due to a particularly complex set of input conditions. Given the nature of the computing devices used in the Cloud infrastructure, the failure of machines during the operation must be taken into account, even though the rate is quite low. The control mechanism block should adopt an effective measure to balance the load by migrating the jobs from one computing node to another in case any of the nodes finish the job early or fails.

Desirable Features.

- Flexibility. For a diverse range of users from different geographical locations, the system must be flexible enough to switch between operations and produce desired outputs without compromising performance. There should be flexibility in the control mechanisms as this determines how the entire system runs. Depending upon the availability of the resources in the system and the requests made by the users, the control mechanism should have the ability to vary and configure the operation of the system to produce the suitable outputs. If any changes in the control mechanisms are required at any instant of time, the control mechanism should be able to be changed without significantly altering any other components of the system[43]. The control mechanisms employed in the system cannot take static or rigid forms as adaptive techniques have to be incorporated to the control mechanisms to make the system operable under any dynamic conditions[44].

- Optimization. Whenever an ensemble of runs for a Geospatial process are carried out, a large amount of computing resources must be utilized[37][45]. These computing resources can be expensive and using them in a non-optimal way can result in a significant waste of resources if used to offer end services. The control mechanism block should employ an effective measure to optimize the computing resources used in each run of the system. The facilitation of the centralized result storage system can help in further optimization of the resources in the system. Filtration and sorting out mechanism can also be helpful for optimization of the resources in the system[46].

- Autonomy and Isolation. The number of the processes that may be run during the implementation of a Geospatial process can be very high. Repeated interaction between the processes can slow make the entire system due to the large-scale exchange of data. Moreover, the operation of the system for Disaster Management is highly distributed and it is desirable to have the least exchange of data between the computing nodes during processing. As far as possible, each run of a simulation in an ensemble in a computing node should be made as independent and autonomous as possible to decrease the overhead and network bottleneck in the system architecture[47]. The control mechanism block should define functionalities to maintain the independent mode of operation.

3.1.3. Cloud Infrastructure

The Cloud infrastructure is the foundational block in the system architecture that eliminates the need of having local computers or powerful servers to be able to simulate a scenario. NDM models require compute-intensive machines to support and run the ensemble simulations and aggregate the results for better interpretation. This block of the system architecture transfers the complexities to the Cloud infrastructure. This tier should provide the foundation to conduct massive computation with huge data sets with advanced networking requirements. The Cloud Computing infrastructure can be chosen from any Cloud service providers as long as the service provides the basic features of the Cloud Computing in terms of scalability, fault-tolerance, security and other related aspects. Based on the functionalities, Cloud infrastructure can be used for different applications listed below:

Functionalities.

- Computational Applications. Geospatial processes and NDM models are complex and the hardware requirements to support these models can be significant, making the local desktops and computers obsolete in terms of time performance. On the other hand, Cloud Computing can create a virtual pool of any number of computing nodes connected together to address the large computational needs of any system. For any Geospatial and Natural Hazard model, Cloud infrastructure can easily handle the computational needs from simple analytical processing to large-scale ensemble runs of simulations. The computing nodes in the Cloud infrastructure can be easily scaled for better utilization of the computing resources. The scaling can either be upwards in horizontal or vertical fashion for compute-intensive applications, or downwards in the same manner for less compute-intensive applications. An additional mechanism can be integrated with the Cloud infrastructure to ensure the optimized utilization of computing resources in terms of cost and time.

- Visualization. A wide range of visualization tools can display the important information and outputs obtained from Geospatial processes and models for disaster management. Depending upon the tools used, the hardware required to support the visualization of the results and information can be significant. As such, Cloud infrastructure can be used to visualize a number of components ranging from simple analytical results to complex statistical result sets obtained as outputs from ensemble runs. Clouds can provide a flexible, scalable and dynamic solution for visualization of different components of various models when it comes to user-focused service models. Customized and sophisticated techniques can independently be integrated into the system to provide quick and complete information to users and authorities for effective decision making. Cloud infrastructure can be used to develop a visualization platform for result data, location-based resources information and resources mobilization for better decision support. The visualization platform over the Cloud infrastructure can compliment the rigorous operations of different aspects of the model in an interactive way.

- Storage. The recent advancement of data collection technologies and new Disaster Management models can result in massive datasets for various operations. Moreover, the nature of frequency of access to these datasets can be irregular as there might be a spike in the access of the disaster data during the peak occurrence periods compared to other times of the year. The near-unlimited capacity of storage of Cloud infrastructure is an ideal solution to address the data intensiveness of Geospatial models. The frequency of occurrences of natural disasters and associated data information can easily generate a huge volume of data that do not just require a storage media but also analytical and complex processing. When a number of users require seamlessly access to the data from different locations, Cloud infrastructure can provide a solid solution for an effectively managed data archive system for any Disaster Management models.

- Data Management. For the implementation of a Disaster Management model, data from a diverse sources have to be collected to be able to run the simulation for producing the relevant and important results. For example, wildfire prediction models require data for topography, fuel characteristics and land coverage of the considered area, as well as a range of meteorological information such as wind, air temperate and related factors. As such we require a strong hardware base that can effectively handle all the distributed chunks of data required for the model. Cloud Computing can create a pool of virtually connected data centers for storing massive sets of data. The act of handling and managing the large chunks of data stored over the Cloud can be non-trivial and the effectiveness of data management techniques is determined by how quickly the data can be fetched from the storage for further processing and representation. Because of the distributed architecture of Cloud Computing, effective and advanced data management techniques can deliver faster and accurate representation of data to the concurrent users located at different geographical locations for use in their models.

Desirable Features.

- Scalability. Given the compute-intensive nature of models, the system architecture may require a number of computing nodes over the Cloud infrastructure. Rather than just increase the time taken for the operation to be completed, the Cloud infrastructure should facilitate the easy scaling out of the infrastructure in terms of the number of processing nodes following different constraints set by the control mechanism of the architecture[46]. The trade-off between the vertical and horizontal scaling of the Cloud infrastructure is handled by the control mechanism but, the Cloud infrastructure should have enough resources to provide the system architecture with that capability.

- Performance. It can be critical for specific disaster models to be able to produce results within designated time windows. Whenever such models are offered as end services there are various performance factors such as cost that need to be considered. The performance of the entire service model is dependent upon the performance of the Cloud hardware and hence the performance of the hardware should not just support the operations but also be consistent. The Cloud infrastructure should be able to provide superior performance under any range of service requests by employing proper control mechanisms[14]. The hardware in the Cloud infrastructure should maintain the same level of performance even when subjected to the higher traffic of user requests or tasks.

- Storage. NDM can result in massive datasets from models, sensors and tools[14]. During ensemble simulations this data might have to be held within the Cloud infrastructure. Moreover, the results produced by large number of simulations that run under a Natural Hazard model can significantly increase the storage needs of the Cloud infrastructure. The Cloud infrastructure should possess enough storage capacity to be able to address the data-intensiveness of Disaster Management model.

- Ubiquitous Access. Ubiquitous access to the Cloud infrastructure is critical to the entire system architecture as the system aims to offer the different functionalities as services. The access of the data and services should be possible from any location using any web services or APIs using a wide range of devices that have internet connectivity[48]. The system should be able to access the Cloud resources easily so as to execute any necessary processing as required by the users.

- Security. The Cloud infrastructure needs to be secure as it should provide the results of simulation runs of disaster models to concurrent users. The user data should be kept intact and separate during concurrent handling of the user requests with the adaptation of various security measures[49]. The Cloud infrastructure should have security features to maintain the data integrity during the operation of the entire system. New security features and measures can be defined using the control mechanism block.

3.1.4. IoT Network and Fog/Edge Computing

The disaster scenarios can be best represented by different disaster models if the real-time data can be fed into those models. The updated data can help create a better situational awareness during the occurrence of the disasters for more effective response against the disasters. As such, collection of real-time and live data during the emergencies is possible with the evolving technology of Internet of Things(IoT). An extensive network of different kinds of sensors can be created in an affected area to collect as much relevant information as possible. During the occurrence of disasters like fires, the real-time data can be collected from a wide network of different sensors like temperature, wind, humidity, rain and fuel-types and other types of connected devices carried by response teams and people, at a station closer to these devices or at Cloud servers depending upon the communication methods available.

In the proposed solution, Cloud infrastructure provides a robust solution to different disaster-related services in an effective way. This can be hindered during the actual occurrence of the disasters as the communication infrastructure and the regular power supply, on which Cloud services are primarily dependent on, may break down. As such, the new paradigms of computing, edge and fog computing have been considered under the umbrella of Cloud computing for more time sensitive and critical services during the emergencies. In the proposed solution, based on the complexity and sensitivity of the services, processing of the data retrieved from the sensor can be pushed closer to the sensor network to trigger different actions prior or during the disasters. Specially, during the event of the disasters with limited connectivity and power supply, the end devices like smart phones and routers can be used to create an ad-hoc network to collect critical data and perform computations to determine an effective way of responding to the emergencies. Moreover, whenever possible, the on-premise computing devices and local supercomputers or similar High Performance Clusters (HPCs) can be used. All the data and operations upheld at end or local devices because of limited connectivity, power supply and response time should be forwarded to Cloud infrastructure for a long-term storage and more intensive computation to further assess the disasters.

3.2. Effective Use of Proposed Solution

The main idea behind the proposed Cloud-based solution is to enable different functionalities of natural disaster management as end services to be used by different actors (users) during various phases of the disasters. Various studies[50],[45],[51] have proved that the cloud-based solutions are more cost-effective than the on-premise systems for running disaster prediction models. Moreover, in addition to the sequential operation of the disaster simulations in an on-premise setup, if the simulations are parallelly executed over the Cloud as proposed in this work, the prediction results can be obtained in less time, thus giving us more time for better preparedness against the disasters[31]. Given the cost-effectiveness and efficiency of the proposed solution, the government should be willing to pay for the expenses of the solution. The description of how the proposed Cloud-based solution can be effectively used during various phases of disaster is given below.

3.2.1. Prevention

For the disasters whose occurrences can be prevented, the complex disaster simulations based on different disaster models can be run over the Clouds as end services to determine the key causes of the disasters[52][53]. Accordingly, measures can be prioritized in a particular region for preventing the disaster. An archive of information system can be maintained using Cloud infrastructure that provides a comprehensive coverage for all the disasters[54][55]. Alerting and notification services can be developed based on the processing and analysis of the data collected using different sensors, over Cloud[38].

3.2.2. Preparedness

During the preparedness phase, running disaster simulations for the determination of risk metrics[56], analysis of crowdsourced data[54][57], enhanced visualization and monitoring of different aspects[58][59], processing of sensor data for regular alerts and storage of crucial real-time and live data[60][61] can be done over the Cloud environment to stay better prepared against the disasters. Especially for the preparedness against the disasters, local computing resources, supercomputers or similar HPCs can also be used in a hybrid fashion[62][63][64].

3.2.3. Response

For the better response, the co-ordination of the entire rescue and search operation can be centered around the Cloud infrastructure with remote operations, information collection, intuitive visualization, meaningful monitoring and efficient evacuation plans [65][54][38][66][64]. Depending upon the nature of the disasters, proper evacuation strategies and mobilization of response units can be achieved through the computations carried over the Clouds[67]. For some forms of the disaster like fire and flood, even the general public (at different locations closer to the disaster-affected location) can use different services under the proposed solution to run disaster simulations to develop more effective strategies at an individual level. But, for some forms of disasters, the communication infrastructure and reliable power supply may be interrupted, making the access to Cloud services difficult. Nevertheless, the effective use of the proposed solution can be ensured by overcoming the communication breakdown during the disasters and using Cloud infrastructure in conjunction with IoT network, edge and fog computing as described in detail below.

Overcoming Communication Breakdown during the Disasters. Some forms of disasters can completely wipe out the infrastructure required for any Cloud services to be operational at the affected location. This is true for the private clouds whose data centers are located in the affected areas. For a public cloud infrastructure, geographically diversified location of the data centers, replicas of the data collected and the remote operation can create a more robust infrastructure to coordinate the activities during the actual occurrence of the disasters[31]. As such, even with no or unreliable power supply during the disaster, the public Cloud infrastructure at a distant location can be used to process and simulate different disaster scenarios to produce critical results that could be relayed to the affected areas for better rescue operations. There are various studies that have tried to enhance the robustness of the communication infrastructure before and during the occurrences of the disaster. In the pre-disaster scenario, a redundant network design, enabled by improved fault tolerance and several backup links, has been discussed in [68] and [69] for survivable communication networks. During the disasters, rapid emergency networks, based on portable nodes and end-user devices, can be created to enhance the connectivity[70]. The internet connectivity can be made possible using satellite, optical fibers, robust wireless gateways and vehicular access points by creating a mesh network based on these transportable nodes[71]. An ad-hoc network created by different techniques involving the mobile devices can ensure the connectivity during the disasters for critical communication[72]. Moreover, the unmanned aerial vehicles (UAvs) like drones[73] and Autonomous networked robots[74] can play a significant role in providing the connectivity to an affected area so that the critical data can be transferred to the central infrastructure of Cloud for further assessments and planning. The results obtained from the further assessment in Clouds can be disseminated to the affected area for more effective steps during the disaster, similar to the faster than real-time evacuation steps during emergencies calculated over Clouds[75].

Conjunction with other Computing Paradigms. The proposed solution is an overview of how different disaster-related services, from complex ensembles to evacuation plans, can be centered around the Cloud infrastructure along with different other technologies(IoT, Fog and Edge) for better preparedness and response during the disasters. For critical and time-sensitive services during the occurrence of the disasters, the end devices in fog and edge computing should provide various services related to alerting, evacuation plans and rescue resources mobilization. The intensive sensor networks in an IoT environment can help offer different disaster-related services with real-time and live data to best reflect and respond to the disaster scenarios. For the utmost efficiency of the proposed solution, different operations and services have to carried out in different devices under various computing paradigms based on complexity, time-sensitivity and critical nature. Cloud Computing still stands as an inseparable component that is required even for other computing paradigms for better assessment and interpretation of the situations. An overview of using Cloud Computing in conjunction with other computing paradigm for more effective disaster management based on different factors is given in Table 2.

4. Current Research Trends

This section examines and categorizes work done in using the foundation of ICT in relation to NDM and the adaptation of Cloud Computing for supporting the different aspects of disaster models. There have been a number

Table 2: Scenarios for effective use of Proposed Solution

Factors	Level		
	Low	Medium	High
Compute-Intensive	Fog/Edge	Fog/Edge/Cloud	Cloud
Data-Intensive	Fog/Edge	Cloud	Cloud
Time Critical	Fog/Edge	Fog/Edge/Cloud	Cloud
Internet Connectivity	Fog/Edge	Cloud	Cloud
Reliable Power Supply	Fog/Edge	Fog/Edge	Cloud

of studies carried out to provide a range of end services related to natural disasters using various features and tools of ICT including Cloud Computing. Figure 5 represents how the related works are categorized into different headings to reflect the current research trends. The related works are explained in detail under different categories as follow:

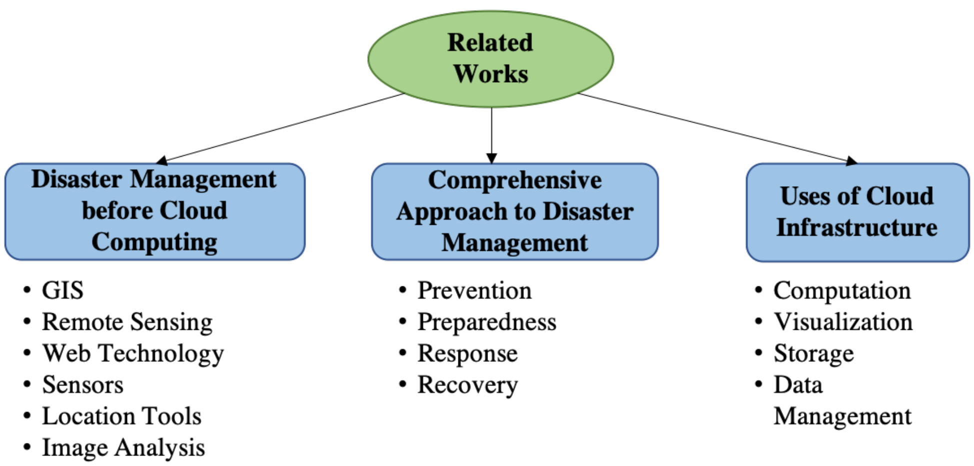

Figure 5: Categorization of Related Works

4.1. Disaster Management before Cloud Computing

A number of ICT tools ranging from Geographical Information System (GIS) tools to Image analysis were used to address various aspects of disaster management before the advent of Cloud Computing. GIS tools were used to produce and present the results obtained after spatial processing and analysis with additional geographical information for a better decision support.

Pidd et al.[76] developed a prototype simulator capable of providing spatial decision support to emergency planners by integrating the geographical information within the simulator. Yong et al.[77] used GIS in conjunction with web technology to develop a decision support tool for identification of effective response strategies to strong earthquakes and assessment of expected damages and losses. Wex et al.[67] proposed a decision support model based on Monte-Carlo heuristics using geographical information for NDM that minimized the sum of completion times of incidents weighted by the severity of the incidents. The model was efficient during the emergency operations for allocation of available rescue units to any emergency incidents and scheduling the processing time of those incidents. Van Westen[78] demonstrated how Geographic Information System can be coupled with Satellite Remote Sensing to develop effective disaster management tools for prevention, preparedness, relief and reconstruction at different stages of the disasters. Laituri and Kodrich[79] added Internet GIS into the system to increase the effectiveness of the disaster response and management after high magnitude disasters. Jeyaseelan[53] validated the efficiency of using GIS intefrated with the Remote Sensing for early warning, real-time monitoring and damage assessment in any events of flood and drought. Manfre et al.[80] and Montoya[55] demonstrated the effectiveness of using GIS along with Remote Sensing and related technologies for better disaster and urban risks management respectively. Cutter[81] explained to what extent geo-information Science can be used by practitioner community for post disaster management.

The use of Satellite Remote Sensing was widely adapted to monitor the disasters and derive critical information before, during and after the occurrence of the disasters. Kerle and Oppenheimer[82] verified the ascendancy of Satellite RS over the use of sensors for better disaster management in Lahar. In a study carried out by Voigt et al.[83], efficient image analysis techniques were carried out on the multiple source satellite data to generate rapid maps for disaster and crisis management support. The study also used the satellite data for rapid impact assessment after different disasters occurred at different corners of the earth. The work done by Tralli et al.[84] demonstrated how satellite Remote Sensing data can be effectively used in conjunction with multiple modeling for forecasting and visualizing the results for better decision support in case of the occurrence of natural hazards such as earthquakes,volcano, flood,landslide and coastal inundation hazards. The works [78], [53] and [80] explain the effectiveness of disaster management when Remote Sensing was coupled with other technologies such as GIS and Global

Navigation Satellite System(GNSS). Montoya[55] developed a cost effective and rapid method of collection for an inventory based on Remote Sensing, global positioning system (GPS), digital video (DV) and GIS for urban risks management.

Web technologies have been used to accommodate different disaster related services for easier access and limited computation. Yong et al.[77] used web-technology for hosting the decision support system for disaster management that facilitated easier user access to the system. Different types of sensors were used to gather as much information as possible to derive better understanding of the disasters. Kerle and Oppenheimer[82] investigated the efficiency of using optical and radar sensors as tools for disaster management for lahars. 'People as sensors' was used as a concept in the system for effective response and management after high magnitude disasters. Geographic location information tools such as GPS and GNSS were used in [80] and [55] to annotate additional information of location to the information collected from other sources such as Remote Sensing and GIS tools. Efficient image analysis techniques were used in the work[83] to generate rapid maps on satellite data for better crisis management support. The summary of the ICT tools used for disaster management is represented in Table 3:

4.2. Aspects of Disaster Management

This section categorizes the research works based on different aspects of NDM. There are different aspects of natural disasters where activities can be focused in various ways so as to reduce the impacts of the natural disasters. Starting from the prevention of the occurrence of the disasters to the assessment of the damages caused by the disasters, every aspect is equally important to build effective strategies for better disaster management.

4.2.1. Prevention

Researchers have relied on risk identification, historical information, monitoring based on data processing and analyses and simulation of processes for preventing the actual occurrences of the disaster such as flood and droughts. The studies by Yu and Kim [52] as well as Jeyaseelan[53] identified the vulnerable regions for possible floods and droughts and helped concerned authorities to take effective measures to prevent the occurrence of the disasters. The historical information about the occurrences of the disasters was emphasized to make effective strategies to prevent the occurrence of flooding events by Wan et al. [54] and health issues related disasters by Shen et al. [85]. The

Table 3: Disaster Management Solutions before Cloud Computing

ICT Tools	Purpose	Related Works
GIS	Better Decision Support	Pidd et al., 1996[76], Wex et al., 2014[67], Van Westen, 2000[78] Laituri & Kodrich, 2008[79], Cutter, 2003[81] Jeyaseelan, 2003[53], Manfre et al., 2012[80], Montoya, 2003[55]
Remote Sensing	Monitoring and Data Collection	Kerle & Oppenheimer, 2002[82], Voigt et al., 2007[83], Van Westen, 2000[78], Tralli et al., 2005[84], Jeyaseelan, 2003[53] Manfre et al., 2012[80], Montoya, 2003[55]
Web Technology	Service Hosting and Wide access	Yong et al.,2001[77]
Sensors	Information Collection	Kerle & Oppenheimer, 2002[82], Laituri & Kodrich, 2008[79]
Location Tools	Advanced Monitoring	Manfre et al., 2012[80] Montoya, 2003[55]
Image Analysis	Map Generation	Voigt et al., 2007[83]

extensive processing and analyses of multiple data were key to form effective strategies in the system proposed by Jiang et al.[86], Liu et al.[33] and Montoya[55]. The data processing framework proposed by Jiang et al.[86] facilitated convenient and highly available processing of the forest pest control data to build an effective strategy for forest pest control. The monitoring system developed by Liu et al.[33] focused on prevention of the disasters caused by magnetic storm facilitated by power system data, geomagnetic data, satellite data and other earth space observation data and their processing over the Clouds. Montoya[55] explored the use of low cost and rapid method of data collection for development of inventory based on combination of various technologies such as RS, GPS, Digital Video and GIS with multistage operations and analysis for prevention of disaster situations. Eriksson et al.[87] developed a Cloud-based architecture for simulating the pandemic influenza so as to be able to prevent the chaotic environment caused by the influenza.

4.2.2. Preparedness

The research works have adapted various methods ranging from monitoring enabled by geovisualization to running simulations for predicting the instants of disasters. The disaster monitoring enabled by visualization of data collected from different sources provided crucial information to general public about the spread of the disasters and helped them prepare against the impacts of the disaster. The web-based visualization service set up by Australia based on the Sentinel satellite [58] provides graphical information of wildfire events occurring all over Australia with well-categorized indexes based on time to general public. The monitoring system developed by Zou[88] facilitated rapid information extraction from satellite RS data so as to stay prepared against possible disaster scenarios. Bohm et al.[89] proposed geovisual analytic solutions in public health sector for better planning processes to prepare and tackle the emergency situations. The Climate Engine developed by Huntington et al.[59] helped in visualization of climate data in an interactive GUI so as to stay prepared against any disasters caused by extreme climatic conditions. The work done by Tralli et al.[84] focused on the use of satellite RS data for construction of Geospatial models for monitoring the disasters for effective preparation against those disasters.

Many early warning systems have been developed to warn the people about the possible dangers of disasters and encourage them to stay alert [61], [60], [65], [38], [90], [53]. The system devised by Al-Dahash et al.[91] facilitated the early warning system based on efficient communication for preparing against dangers caused by terrorism in Iraq. Puthal et al.[60] presented a big data stream framework that supported the emergency event detection and generation of the alert by effectively analyzing the data stream. Rossi et al.[65] introduced a service-oriented Cloud based architecture that was capable of issuing early warning during the events of disasters. The web-based platform VirualFire [38] had the capability of issuing early warning in the event of a fire to general public for staying prepared against the disaster. The community-based Cloud system proposed by Li et al.[90] facilitated the issuing of early warning of disasters that was helpful in building preparatory strategies to minimize the impacts of the disaster. The study carried out by Jeyaseelan[53] was capable of issuing early warning for general public in case of any events related to flood and drought for better preparedness.

The importance of regular updates about the disaster along with regular exchange of information between different entities was highlighted in a system called CyberFlood developed by Wan et al.[54] that incorporated crowd sourcing technology for providing fresh updates on flooding events to enable general public to stay prepared against any water-related disasters. Furthermore, the architectural design of communication network proposed by Ali et al.[92] focused on effective flow of information for better preparedness against the disasters. The integrated approach devised by Zlateva et al.[93] performed the risk assessment of natural disasters to calculate the probability of occurrence of a particular disaster for the effective preparedness. The outspread of various disasters can be predicted to take better informed decisions to stay prepared against the perilous disasters. SparkCloud developed by Garg et al.[**?**] facilitated the users to predict the spread of bushfires so as to form preparatory strategies to minimize the impacts of the disasters caused by fire. Huang et al.[45] formulated the forecasting of dust storm through ensemble run of the model to contribute to the preparedness against the emergency situations caused by dust storms. Li et al.[51] facilitated the run of ensemble simulation of different Geospatial Science models over the Cloud to predict the outburst of various disasters so as to develop effective preparatory strategies against the disasters. The Sentinel Hotspots system [58] maintained by Geospatial Science Australia in the Cloud environment provides visual information to public about the actual occurrence of the bushfire events in different time resolutions.

4.2.3. Response

Studies have focused on regular and quick information collection, better communication between response teams, efficient mobilization of rescue units and simulation of risks and evacuation plan for more effective response to the disasters to keep the loss of lives and physical structures to minimum. Wex et al.[67] proposed a decision support model based on different heuristics for effective allocation and scheduling of rescue units that formulated and solved the problem through the minimization of the sum of completion times for different events of natural disasters weighted by their severity.

Regular collection of information is necassary while responding to the occurrences of the disasters and many previous studies have examined this in the context of disaster response. The Collaborative Knowledge as a Service (CKaaS) proposed by Grolinger et al.[94] focused on the collection and integration of diverse sources of data over the Cloud environment for the disaster response management. Zou[88] devised a disaster monitoring system by proposing an interoperable framework to integrate a distributed model and data for rapid information extraction. Kerle and Oppenheimer[82] established the superiority of satellite imaging over optical and radar sensors for facilitating better disaster response management from lahars. The work done by Van Westen[78] advocated the use of Remote Sensing and geographic information systems for various phases of disaster management. A software called ERIC[95] was developed to automate situation reporting during any emergency situations by collecting data from a wide range of sources. The collected data was visualized using a web interface to respond in better ways against any disasters. that weKlauck et al.[96] proposed flexible post-disaster management facilitated by continuous monitoring enabled by sensor data and interaction between the observers over the Cloud. The software architecture proposed by Rossi et al.[65] used data from different sources to produce observations for authorities and responders for Emergency Response services. Li et al.[90] maintained information repository for effectively handling the disaster response management with updated information collected from multiple sources. Voigt et al.[83] explained the use of satellite data collected from multiple sources and efficient image analysis for production of rapid-maps for better disaster and crisis management support. Manfre et al.[80] highlighted the use of technologies such as remote-sensing, GIS and GNSS for improvement in construction of effective emergency plans for post-disaster management at different levels. Based on the analysis of satellite RS data Tralli et al.[84] carried out reconstruction of land surface maps based on historical data for better mitigation and management in post-disaster situations. The users of cyberFlood[54] can access information about actual occurrences of floods from the data collected through crowd-sourcing technology. The work done by Jeyaseelan[53] highlighted the importance of Remote Sensing and GIS for real-time monitoring to provide rapid updates during the occurrence of the disasters such as floods.

Several studies have emphasized the importance of effective communication between different entities involved in disaster management for better disaster response [92], [38], [97], [91]. Ali et al.[92] proposed a network architecture with reinforced layers for effective communication to facilitate better post-disaster management. The VirtualFire developed by Kalabokidis et al.[38] incorporated web-based platform to share and utilize information and tools among firefighters for better coordination of firefighting efforts in the events of the fire. The metamodel for disaster management proposed by Othman and Beydoun[97] described how the semantic domain models could be built into an artifact for better knowledge sharing thereby facilitating the combination of different activities to manage the disaster on the hand in better ways. The work done by Al-Dahash et al.[91] provided concerned agencies to make better decision by providing properly managed communication during the emergency situation caused by terrorism in Iraq.

The simulation of risk scenarios, evacuation plans and risk assessment in various studies can provide important information for making better decision for responding to the disasters. Qiu et al.[98] developed a smart evacuation system over the Clouds using smart phones and data centers to facilitate emergency decision system for faster disaster response. Alazawi et al.[99] proposed the modeling of impact of various disasters on the real transportation system of the cities for improving the flow of the traffic and smooth evacuation during the events of disasters. Pidd et al.[76] developed a prototype of decision support for use by emergency planners for effective evacuations from the disaster areas in the post-disaster scenarios. The stakeholders could input different desired risk scenarios into the platform developed by Aye et al.[100] for possible mitigation measures for better disaster response management. The risk assessment result obtained in the integrated approach proposed by Zlateva et al.[93] could provide the government with crucial information for taking more informed decision regarding the mobilization of the resources in post-disaster scenario.

4.2.4. Recovery

The use of an actuarial model combined with Remote Sensing has been used to assess the damages caused by disasters such as flood and droughts. The aggregated loss after a disaster could be accounted for using an actuarial model in the approach explained by Zlateva et al.[93] which was helpful in distribution of the available fundings for the population affected by the disasters. Jeyaseelan[53] emphasized on the use of Remote Sensing for quick damage assessment of drought and flood disasters.

4.2.5. Holistic Aspects of Disaster Management

Some previous work has addressed the facilitation of a range of services before, during and after the occurrence of a disaster, thereby addressing every aspect of disaster management. Adam et al.[101] examined the combination of social media and spatial computing for effective disaster management with different services including issuing alerts, data streaming, location services and data services. Habiba and Akhter[102] proposed a Cloud-based framework for enabling multiple services to facilitate better and effective disaster management. Tralli et al.[84] highlighted the importance of satellite RS data in reconstruction of land surfaces based on recent history for predicting the hazards due to various disasters such as flood, landslide, flood and coastal inundation for preparation, mitigation and management of the disasters. Manfre et al.[80] highlighted the importance of remote-sensing, GIS and GNSS for effective NDM through the establishment of spatial data infrastructure and participation of organization and government to facilitate proper exchange of information. Bessis et al.[103] explained the visionary opportunity in integrating various emerging paradigms including grid, Cloud, pervasive and situated computing for a collective intelligence model for effective disaster management. Laituri and Kodrich[79] introduced the 'people as sensors' concepts using online disaster response community for effective and quick circulation of information using blogs and pictures for better response during every phases of natural disasters.

A comparative summary of related work based on different aspects of disaster management is shown in Table 4.

4.3. Cloud Infrastructure

The related works are categorized under different categories based on how they have used Cloud environent to address different aspects of the disasters as follow.

Table 4: Categorization of Related Works based on various aspects of Disaster Management

Aspects	**Methods**	**Related Works**	**Disasters**
Prevention	Risk Identification	Yu et al., 2018[52], Jeyaseelan, 2003[53]	Health Disaster,
	Historical Information	Wan et al., 2014[54], Shen et al., 2012[85]	Floods, Droughts
	Data Processing & Analyses	Jiang et al., 2010[86], Liu et al., 2012[33] Montoya, 2003[55]	Disaster Risks Forest Pest Disaster,
	Simulation	Eriksson et al., 2011[87]	Magnetic Storm
Preparedness	Monitoring	Australia, 2018[58], Zou, 2017[88] Bohm et al., 2011[89], Huntington et al., 2017[59] Tralli et al., 2005[84]	Dust Storm,
	Early Warning System	Al-Dahash et al., 2017[91], Puthal et al., 2016[60] Rossi et al., 2017[65], Kalabokidis et al., 2013[38] Li et al., 2011[35], Jeyaseelan, 2003[53]	Fire, Terrorism, Flood, Health Disaster, Other Risks
	Effective Communication	Wan et al., 2010[54], Ali et al., 2015[92]	
	Risk Assessment	Zlateva et al., 2013[93]	
	Simulation	Garg et al., 2018[?], Huang et al., 2017[17] Li et al., 2017[51]	
Response	Rescue Unit Mobilization	Wex et al., 2014 [67]	
	Information Collection	Grolinger et al., 2015[94], Zou, 2017 [88] Kerle & Oppenheimer, 2002[82], Van Westen, 2000[78], Klauck et al., 2011[96] Rossi et al., 2017[65], Li et al., 2011[90] Voigt et al., 2007 [83], Manfre et al., 2012[80] Tralli et al., 2005[84], Wan et al., 2014[54] Jeyaseelan, 2005[53], ERIC, 2018[95]	Flood, Fire Droughts,
	Effective Communication	Ali et al., 2015[92], Kalabokidis et al., 2013[38] Othman & Beydoun, 2013 [97] Al-Dahash et al., 2017[91]	Other Risks
	Evacuation Plan	Qiu et al., 2014[98], Alazawi et al., 2012[99] Pidd et al., 1996[76]	
	Risk Assessment\Simulation	Aye et al., 2015[100], Zlateva et al., 2013 [93]	
Recovery	Model	Zlateva et al., 2013[93]	Flood, Droughts
	GIS and RS	Jeyaseelan, 2010[53]	Disaster Risks

4.3.1. Computational Application

Ensemble Simulations. Some Geospatial and hazard models require a large number of simulations to be run to derive statistical metrics rather than a single deterministic result. This approach is often used when inputs into models are subject to uncertainty and can only be expressed as probabilistic distributions rather than fixed quantities. Examples include the amount of rainfall over a particular area for flood models, or weather conditions in wildfire models. By sampling from a probabilistic distribution and running an ensemble of simulations the results can be combined through a reduction step into a probabilistic output, for example for risk metrics such as probability of flooding or wildfire impact. The Cloud environment is well-suited to support compute-intensive ensembles of hundreds to thousands of simulations. However, few studies have used Cloud infrastructure to run ensembles for predicting the outspread of various disasters. Garg et al.[**?**] examined the possibility of using Cloud Computing for ensemble run of Geospatial Science models by developing SparkCloud for the wildfire prediction software Spark. Huang et al.[45] verified the readiness of Cloud infrastructure for ensemble run of complex dust forecasting model by deploying the parallel mode of dust model over Amazon EC2 foundation with reduced costs as compared to local resources. Li et al.[51]developed a MaaS that conducted an ensemble run in parallel with single requests from the users. All the required data for the ensemble run are uploaded by the users using the web-interface. A cyberinfrastructure based geographic information system was developed by Behzad et al.[37] that was able to support ensemble run of groundwater system modeling over the Cloud environment provided by Microsoft Windows Azure Cloud Platform.

Simulation/Modeling. Various studies that have implemented models within the Cloud environments to simulate different aspects of disaster management. The smart evacuation system proposed by Qiu et al.[98] performed various modeling of evacuation plan, threats and cities over the Cloud infrastructure. Alazawi et al.[99] performed modeling of impacts of disasters on the traffic flow of the city over the Clouds based on the data collected by multiple sources for better disaster response. Eriksson et al.[87] developed a simulator over the Cloud environment of Amazon EC2 to understand the process of outbreak of pandemic influenza at a particular place. Kalabokidis et al.[38] also simulated the spatiotemporal spread and intensity of a forest fire using FARSITE [4]. Pajorova and Hluchy[104] developed a platform for HPC over the Cloud environment for complex Earth and astrophysics simulations. Ji et al.[105] used Clouds to implement a Geospatial workflow application based on the weights of Evidence Method Metallogenic Prediction for mineral prediction with improved execution time and scalability. Vockler et al.[106] developed an application to process the astronomical data released by Kepler project across the multiple Clouds of FutureGrid, NERSC's Magellan Cloud and Amazon EC2 using the Pegasus Workflow Management System and generate computationally complex periodograms of the data.

Geospatial/Data Analysis. Cloud computing has been used extensively in Goespatial processing for calculating various indexes, spatial and statistical processing and data analysis for better decision support. The computational task of calculating standardized precipitation index, drought index and vegetation index was carried out by Yu et al.[52] within the Cloud environment. Zou[88] provided a Cloud solution of MapReduce for data analysis of massive RS data including the preprocessing such as radiometric correction, geometric correction, mosaic and fusion and information extraction processes such as classification, transformation and index calculation. Zlateva et al.[93] used the Cloud infrastructure to perform risk assessment of the natural disasters using a joint application of fuzzy logic models and an actuarial model. Various biodiversity indices at different resolutions were calculated using the marine life data in the system developed by Fujioka et al.[108]. VirtualFire [38] computed fire ignition probability for identification of high-risk areas.

Wang et al.[111] used the Cloud infrastructure to perform high performance and distributed spatial interpolation of hugely massive spatiotemporal data sets that included climate data, census survey data and Remote Sensing images. The study carried out by Golpayegani and Halem[107] developed a high end compute clusters over the Cloud infrastructure with a distributed file system and MapReduce framework integrated into the cluster for speedy large-scaled processing of largely massive Remote Sensing datasets. A number of Geospatial analysis and statistical processing was facilitated in the work done by Huang et al.[17] who integrated diffferent Geospatial models into their system. The HCC platform was capable of supporting ensemble runs of Geospatial models which was validated by run of dust storm forecast model over the primary Cloud infrastructure of Amazon EC2 Clouds. Al-Dahash et al.[91] maintained a separate layer in the Cloud environment to perform various processing and analysis over the data collected in the database to draw significant conclusions for better disaster management. A

Table 5: Categorization based on different computation applications

Computation Applications	Related Works	Purpose/Aspects	Deployment Models/ Cloud Providers
Ensemble Simulations	Behzad et al., 2011[37], Garg et al., 2018[?] Li et al., 2017[51], Huang et al., 2013[45]	Wildfire, Dust Storm, Ground Water System, Geospatial Models	Public Clouds, Nectar Cloud, Azure Cloud Platform Amazon EC2
Simulation/ Modeling	Alazawi et al., 2011[99], Eriksson et al., 2011[87] Kalabokidis et al., 2013[38], Qiu et al., 2014[98] Pajorova and Hluchy, 2011[104], Ji et al., 2012[105], Vockler et al., 2011[106]	Earth Simulations, Evacuation Disaster Impacts & Outbreak, Mineral Prediction Astronomical Applications	Public Clouds Private CLouds Amazon EC2
Geospatial/ Data Analysis	Yu et al., 2018[52], Di Martino et al., 2011[50] Pajorova and Hluchy, 2011[104], Zou, 2017[88] Wan et al., 2014[54], Montgomery et al., 2010[36] Golpayegani and Halem, 2009[107] , Fujioka et al., 2012[108], De Luca et al., 2017 [109], Wan et al., 2018[110], Li et al., 2011[35] Wang et al., 2010[111], Huang et al., 2017[17] Al-Dahash et al., 2017[91], Bohm et al., 2011[89] Zlateva et al., 2013[93], Huntington et al., 2017[59] Liu et al., 2012[33], Kalabokidis et al., 2013[38]	Indexes Calculations, Spatial Interpolation, Statistical Processing, Data Classification, Climatological Calculations, Risk Identification	Public Clouds Private Clouds Amazon EC2

global flood infrastructure built by Wan et al.[54] used a Google chart API for creating analytic chats for statistical analysis of flood events. Moreover, the system classified the data into different levels based on severity and fatalities of the flood. The environmental monitoring developed by Montgomery et al.[36] performed various processing of Geospatial data for prediction of the changes in various environmental resources so as to ensure proper adaptation for sustainability. Li et al.[35] used Cloud infrastructure to perform various complex Geospatial computing tasks such as FCD query, FCD map matching and speed computation for roadlinks for urban traffic monitoring. The power grid storm disaster monitoring system developed by Liu et al.[33] used the features of Cloud Computing to solve the processing difficulties associated with largely massive geomagnetic data, satellite data and other earth space observation data.

A geovisualanalytics system proposed by Bohm et al.[89] in the public health sector implemented an innovative geo-business intelligence methods and procedures of public heath over the Cloud for better decision support in planning and analysis processes. Climatological calculations and statistical analyses were carried out on the climate and observation data in the climate engine [59]. De Luca et al.[109] used Cloud infrastructure to form a processing chain of differential Synthetic Aperture Radar (SAR) interfermetry (DInSar) Parallel Small Base-line Subset (P-SBAS) for unsupervised processing of large volumes of SAR data. The processing of large volume RS data was dealt with using Virtual Processing System for RS (VS-RS) over the Cloud in pipsCloud [110].

A comparative analysis of use of Cloud Computing for different computational applications is given in Table 5.

4.3.2. Visualization

A wide range of visualization techniques and functionalities have been offered over Cloud infrastructure in conjunction with web technologies for better interpretation of spatial results obtained after computational processes. Interactive mapping tools, advanced animations and 3D visualization have been integrated along with Cloud technologies to provide elaborated and classified information about disasters to take better informed decisions. Moreover, a visual interface hosted over the Cloud provides users of the system the ability to customize and keep track of any processes in operation. Categories of functionalities and support through the use of different visualization methods are further described as follow:

Interactive Mapping Services. The mapping tools used in various studies enabled better understanding of the results obtained after analysis and simulation. Researchers have extensively used a wide range of interactive mapping tools to better visualize the processes that govern different disasters and understand the possible damages caused by those disasters. The studies have made use of existing mapping tools, such as the Google Maps API, while some studies have integrated mapping services of servers such as TeraGrid, and GeoServer. Some of the studies offered real-time mapping services for various Geospatial processes while some offered advanced capabilities by integrating mapping tools into the system after completion of simulation runs or analyses. The related works are categorized into two categories based on their real-time mapping capabilities as follow:

- *Real-Time Mapping Services.* The Sentinel Hotspots Australia and AUSCORS Australia, 2018[58] built by GeoScience Australia used Cloud infrastructure to develop an interactive visualization interface for bushfire events and 1 Hz data streaming from GNSS stations respectively throughout Australia, Antarctica and the Pacific. Wan et al.[54] used a public Cloud-based flood cyber-infrastructure to develop a tool called CyberFlood that could collect, organize and manage global flood data for providing real-time location-based eventful visualization to authorities and the public. The visualization enabled by Cloud Computing included various statistical and graphical capabilities. They used the Google Map API and interactive combination of color codes to represent data under different categories for concise and useful information related to the floods. Montgomery et al.[36] integrated a collaborative visualization along with mapping tools in the user interface of the system for visualization of data for monitoring. The traffic surveillance system described by Li et al.[35] evaluated the utility of Cloud Computing for visualization of urban traffic data obtained after computing tasks namely Floating Car data (FCD) query, FCD map matching and speed computation for road links using different interactive map tools. The system described by Li et al.[90] used a web-based interface powered by mapping services to enable the users to access information, collaborate and communicate efficiently. The work done by Zou[88] proposed a web platform for disaster monitoring where users could visualize the data produced over the portal using maps or download the files in KML or vector file format.

- *Non Real-Time Mapping Services.* Ji et al.[105] incorporated interactive mineral maps for visualization of results obtained after relevant data analysis. Yu et al.[52] used the Cloud environment for visualization of processed data with mapping tools integrated into the system for better understanding of the results. The web-interface in the HCC developed by Huang et al.[17] was capable of displaying the results obtained after spatial analysis or run of Geospatial models using maps. Qiu et al.[98] used maps of a city integrated with results obtained from evacuation model to visualize the evacuation plans. Alazawi et al.[99] made use of interactive maps to visualize the optimized plan for smooth evacuation and better flow of traffic during the events of disasters. Fujioka et al.[108] used a mapping engine powered by GeoServer 2.1 to interactively visualize the search results obtained from the marine life census system maintained over the Clouds. Eriksson et al.[87] facilitated the visualization of simulation results through a simple easy-to-use GUI interface enabled with mapping service in the Cloud-based simulator built for pandemic influenza. Bohm et al.[89] facilitated the visualization of important health data over the Clouds in a scalable manner through the use of JavaScript and HTML along with XML to form a map widget for better understanding. The service layer in Service Oriented Architecture (SOA) proposed by Rossi et al.[65] used a website to geographically and interactively visualize all data handled by service layer in a mapping layout. The visualized data could also be downloaded in different user formats as desired by the users in the system. Li et al.[51] used various interactive visualization tools to display the output of ensemble run of the Geospatial models using different maps in the Cloud environment without downloading the output files. VirtualFire[38] used Bing Map Services and other APIs as web services for interactive visualization of fire spread and weather data. De Luca et al.[109] used advanced mapping services for visual representation of geographical regular grid and deformation velocity maps generated by P-SBAS processing. Wang et al.[110] used interactive map services in their web-based interface for visualization of the data obtained after user queries. The Cloud environment was used to visualize the disaster data sets and information collected over time by Al-Dahash et al.[91] for better decision support.

Animations and Advanced Visualization. Somestudies have utilized the capabilities of Cloud Computing to build advanced animations, rendering of data in 3D and facilited advanced visualization in augmented reality. The HCC system developed by Huang et al.[17] can interactively visualize results after spatial analysis using animations. GI-Solve [111] integrated visualization services supported by TeraGrid into a system for spatial visualization of data through self-guided user interfaces. Qiu et al.[98] used advanced visualization features over the Cloud to display results from evacuation and threat models in 3D scenarios. Montgomery et al.[36] integrated a wide range of communication media including forums, news, blogs and videoconferencing over a custom web page portal for effective collaboration. The study also integrated InteleView for displaying high resolution maps on global scale, in 3D and in real-time. The climate engine [59] allowed users to perform on-demand mapping and time series visualization over the Cloud. Vockler et al.[106] integrated the features of FutureGrid into their system to facilitate the visualization of astronomical data released by NASA. Miska and Kuwahara[112] made use of WebDAV protocol in their Cloud-based system to allow interactivity in a web-based interface and allow users to create, change and move the documents on a remote server. Moreover, the system used OpenSIM to facilitate the visualization of a 3D environment within the web-based interface. Visualization Tool (VT) with advanced displaying capabilities was developed by Pajorova and Hluchy[104] as an e-Science gateway over the Cloud for visualization of simulations related to the Earth and astrophysics. The architecture proposed by Di Martino et al.[50] also integrated augmentation module that received global navigation satellite system (GNSS) data and computed augmented and validated GNSS position for advanced visualization features.

Customization. The visual interface for different Cloud-based systems can be customized based on user preferences and scenarios for the operation of the system. The visual interface allows users to make changes to parameters, timelines and models that are needed to produce relevant results in advanced visual forms. Elements within the user interface can be customized in order to graphically represent various results. Categories of different customisation types for aspects of the user interface are given below:

- *Operation Customization.* The system devised by Li et al.[51] gave users the option of configuring a particular job before initiating the entire run of a model. Users were provided with the ability to customize analytic steps in the climate engine Huntington et al.[59] to produce map and time series results including product types, datasets, variables, calculations and statistics. The stakeholders could input different desired risk scenarios into the platform developed by Aye et al.[100] for possible mitigation measures for disaster management. Huang et al.[113] allowed users to configure the system in any way after an authentication step. Users could customize the monitoring operations through the user interface provided by the system in the work proposed by Montgomery et al.[36]. Shen et al.[85] developed a system where users could find health services for their conditions that was customisable according to their needs through a user interface. Bohm et al.[89] developed a Business Intelligence(BI)-GIS system which offered geovisualanalytic solutions through a customisable user interface. The simulation execution of pandemic influenza could be controlled using a front end interface in Cloud-based architecture proposed by Eriksson et al.[87]. In the Hybrid Cloud Computing (HCC) platform developed by Huang et al.[17], users could customize and choose any desired models from a group of models that were integrated into the platform.

- *Parameters Customization.* SparkCloud [**?**] allowed users to customize wildfire simulations based on ignition locations and timelines. The users of VirtualFire[38] could change the inputs to the system to visualize desired sets of output in the web-based services. The system developed by Ramachandran et al.[114] for distribution of NASA collected datasets allowed users to pick sets of required datasets. Users of the system developed by Yu et al.[52] could customize the location parameters for calculation of different index and visualization of the result data. The users of monitoring system in the work described by Li et al.[35] could change the traffic monitoring based on different parameters.Fujioka et al.[108] developed a marine life census system that could customize a search operation using a number of different parameters for well-refined search results. The cyberGIS framework developed by Wang et al.[111] allowed users to customize various parameters to run the system in desired way for data processing or visualization. The ground water system developed by Behzad et al.[37] allowed user to change ensembles parameters of the model that simulated the flow of ground water.

- *Result Customization.* Many systems have facilitated the customization of visual forms for the representation of the results [59], [50], [52] and [113]. Wan et al.[54] allowed users to select a range of years and causes of the flood in the web-interface hosted by an Apache web server to visualize the customized results. The system devised by Wang et al.[111] was capable of customizing the visualization of analyzed data in a number of ways.

Job Status. The system developed by Huang et al.[17] facilitated the users to keep track of the status of the jobs through a web-based interface. The web-based interface in sparkCloud [**?**] allowed user to monitor the status of the job requested by the users. The web-interface developed by Li et al.[51] could show the status of each jobs that were being processed for the ensemble run of Geospatial models over the Cloud.

Decision Support. Various work has facilitated better decision support at different stages of natural disasters by developing systems delivered over Cloud infrastructure using a diverse range of technologies. The Social Media Alert and Response to Threats to Citizens (SMART-C) developed by Adam et al.[101] focused on developing participatory sensing capabilities for better decision support throughout the life-cycle of a disaster using multiple devices such as smartphones and modalities such as messages, web portals, tweets and blogs. The system architecture proposed by Chavan et al.[115] facilitated the use of Graphical Processing Unit (GPU) for displaying the results of spatial queries by the users. Shen et al.[85] used Clouds for scalable, customizable and robust visualization of health services data obtained after various data processing and clustering steps. The monitoring system developed by Liu et al.[33] and delivered through a wide range of devices allowed user access through a web browser, where desired services could be selected. The outputs of the ensemble run of a ground water model could be saved in Blob Storage after compression and downloaded by the user through a web-based interface in the system developed by Behzad et al.[37]. Habiba and Akhter[102] developed web portals for visualization of data from different modules in a framework proposed for effective disaster management. CUMULUS [114] developed Cumulus-API for a protected GUI allowing users to gain insight into operations taking place and management of the platform.

The categorization of visualization based on tools and functionalities is shown in Table 6:

Table 6: Categorization based on different visualization tools and functionalities

Visualization Tools and Functionalities	**Related Works**	**Tools/Aspect**
Mapping Tools	Australia, 2018[58], Ji et al., 2012[105] , Yu et al., 2018[52] Huang et al., 2017[17], Wan et al., 2014[54] Qiu et al., 2014[98], Alazawi et al., 2012[99] Eriksson et al., 2011[87], Bohm et al., 2011[89] Huntington et al., 2017[59], Li et al., 2017[51] [38], Wang et al., 2018[110] , De Luca et al., 2017 [109] Li et al., 2011[35], Al-Dahash et al., 2017[91] Montgomery et al., 2010[36], Fujioka et al., 2012[108] Di Martino et al., 2011, Rossi et al., 2017[65]	Google Map API, Color Combinations, GeoServer Map Engine, JavaScript, HTML with XML, Bing Maps
Animations and Advanced Tools	Huang et al., 2017[17], Miska and Kuwahara, 2010[112] Di Martino et al., 2011[50], Rossi et al., 2017[65] , Montgomery et al., 2010[36], Qiu et al., 2014[98] Pajorova and Hluchy, 2011[104]	3D Scenarios, InteleView, TeraGrid Augmentation Module FutureGrid, WebDAV, OpenSIM
Customization	Ramachandran et al., 2017[114], Wan et al., 2014[54] , [38], Liu et al., 2012[33] , Li et al., 2017[51] Huntington et al., 2017[59], Garg et al., 2018[**?**] Wang et al., 2010[111], Yu et al., 2018[52] , [35] Behzad et al., 2011[37], Di Martino et al., 2011[50] Montgomery et al., 2010[36], Shen et al., 2012[85] Eriksson et al., 2011[87], Huang et al., 2017[17] Huang et al., 2010[113], Fujioka et al., 2012[108] Bohm et al., 2011[89]	Preferences, Parameters, Risk Scenarios, Deadlines Models,
Job Status	Li et al., 2017[51], Garg et al., 2018[**?**] Huang et al., 2017[17]	Status Bar
Decision Support about Tools	Chavan et al., 2016[115], Li et al., 2011[90] Shen et al., 2012[85], Behzad et al., 2011[37] Habiba and Akhter, 2013[102]	Smart phones, Messages, Web portals, Monitoring

4.3.3. Storage

The almost unlimited capacity of the Cloud infrastructure has been well used in different studies to store large and diverse spatial data sets in Structured and Unstructured forms. Some studies have not clearly defined the form in which the data sets were stored, but the Cloud environment was utilized to store large data sets.

Structured Databases. Most work to date has dominantly used SQL, PostgreSQL and PostGIS to store the spatial data in a structured form. The system developed by Chavan et al.[115] used SQL to store spatial data in the Clouds. Montgomery et al.[36] stored various Geospatial data sets over the Cloud using traditional SQL design to monitor water supply, weather, ocean to predict and adapt to their changes for sustainable development of the environment. Fujioka et al.[108] stored more than 31.3 million observations of marine life data as the Marine Life Census within the Cloud using PostgreSQL and PostGIS, with free access to the users through a Geospatial portal. Rossi et al.[65] used Azure SQL for storing all the user textual information over the Cloud infrastructure. Huang et al.[113] used Postgresql with PostGIS to support spatial datasets for deployment and maintenance of GEOSS Clearinghouse on an Amazon EC2 platform.

Unstructured Databases. The unstructured forms such as NoSQL along with Graph databases, Hadoop Distributed File System (HDFS), Blob services, big-table and geo-databases were widely used to store and analyze the spatial data. Grolinger et al.[94] used Graph databases to represent and store the data using graphical structures with edges, nodes and properties. Huang et al.[17] implemented the concepts of distributed file-system, relational database and NoSQL database over the Cloud infrastructure for holding massively large Geospatial data for different models in the HCC platform. Zou[88] stored massive sets of satellite data over the Cloud in a more distributed approach using HDFS. Wan et al.[54] created the Flood Data Archive within the Cloud using Google Fusion table, containing all flood related data from 1998 to 2008. Grolinger et al.[116] proposed Knowledge as a Service (KaaS) for disaster Cloud data management for facilitating storage of massive datasets related to disasters in relational NoSQL databases. The framework developed by Jiang et al.[86] used HDFS to store massive sets of Geo-data related to forest pest control. Qiu et al.[98] stored the data collected from different sensors installed in disaster prone areas in the data centers for further processing.

Table 7: Categorization based on different structure of Cloud storage

Form	**Related Works**	**Tools**
Structured Form	Chavan et al., 2016[115], Montgomery et al., 2010[36] Rossi et al., 2017[65], Huang et al., 2010[113] Fujioka et al., 2012[108]	SQL, PostgreSQL PostGIS
Unstructured Form	Grolinger et al., 2015[94], Huang et al., 2017[17] , Zou, 2017[88] Wan et al., 2014[54], Grolinger et al., 2013[116] , Jiang et al., 2010[86] Puthal et al., 2016[60], Rossi et al., 2017[65] , Wang et al., 2018[110] Li et al., 2011[35], Schnase et al., 2011[34] , Li et al., 2011[90], Shen et al., 2012[85], Kalabokidis et al., 2013[38]	Graph databases, NoSQL, HDFS, Azure Blob Service, big-table, geo-database Google Fusion Table
No Description	Australia, 2018[58], Ji et al., 2012[105] , Ramachandran et al., 2017[114] Yu et al., 2018[52], Wang et al., 2010[111] , Qiu et al., 2014[98] Miska and Kuwahara, 2010[112], Habiba and Akhter, 2013[102] Bohm et al., 2011[89], Huntington et al., 2017[59] , Behzad et al., 2011[37] Al-Dahash et al., 2017[91], Klauck et al., 2011[96] , Li et al., 2017[51] Adam et al., 2012[101], Liu et al., 2012[33], Alazawi et al., 2012[99]	

Puthal et al.[60] described the storage of the information over the Clouds citing the data-intensiveness nature of the collected data for batch processing in a store-and-process fashion. Rossi et al.[65] used Azure Blob service for storing all the user photos and logos over the Cloud infrastructure. The adaptation of HPGFS along with Hilbert-R+ tree based data indexing in NoSQL database over the Cloud foundation handled the vast amount of unstructured RS data in pipsCloud [110]. Schnase et al.[34] used the framework of Integrated Rule-Oriented Data System (iRODS) to store the disparate data over a distributed architecture. The fire data in VirtualFire [38] was stored over the Clouds using geo-database.The community-based Cloud developed by Li et al.[90] maintained a virtual community database for physical and human resources information and social media database using semantic dimensions for real-time emergency situation through social medias over the Clouds for emergency management. Shen et al.[85] utilized the Cloud infrastructure to develop an effectively managed data archive systems in the form of historical diagnosis database and knowledge base to record medical resources in public health area for developing alternative practices.

No Detailed Information. GeoScience Australia used the Cloud storage provided by AWS to store the massive data related to bushfire events and GNSS observation data in different systems of Sentinel Hotspots and AUSCORS [58]. The system developed by Ji et al.[105] stored the Geospatial data using the Cloud in a native but complex Geospatial type. The data archive developed by Ramachandran et al.[114] optimized the files based on the input configuration and distribution requirements before storing them in the Clouds. Climate precipitation data was stored in the Clouds during the study carried out by Yu et al.[52]. The cyberGIS framework developed by Wang et al.[111] integrated the data storage and management capabilities of middleware workflows into three core data services to handle the massive spatiotemporal data. The SMART-C system devised by Adam et al.[101] stored massive data sets within a Cloud database to keep track of demography, weather, traffic, hospitals, schools and so on for anticipating possible disasters. The framework proposed by Habiba and Akhter[102] used Cloud infrastructure for data record services to facilitate different functionalities after required processing and analysis. The intelligent disaster management system developed by Alazawi et al.[99] used the Cloud to store data collected from multiple sources and locations including the place of an event for better decision support. A high volume of public health data was stored in the

Cloud environment by Bohm et al.[89] to form a business intelligence widget. Large datasets of climate and satellite Earth observations were saved over the Cloud environment for the climate engine [59]. Behzad et al.[37] integrated the Geospatial middleware in the Cloud for storing massive datasets related to ground water flows and maintaining the datasets in an archive over the Cloud infrastructure. Al-Dahash et al.[91] developed database over the Clouds to store all the information about the terrorism collected from multiple sources for further processing and analyses. Klauck et al.[96] stored the information over the Cloud to enable the collaborative work and reduce the acquisition and maintenance costs. The MaaS framework proposed by Li et al.[51] used data servers over the Clouds to store the large number of output data produced after ensemble run of various Geospatial models. Miska and Kuwahara[112] developed an innovative idea to use the features of Cloud Computing to start project management framework by maintaining International Traffic Database project over the Clouds with new possibility of handling the entire project publishing and communication at a place. Liu et al.[33] used the Cloud infrastructures to store massively large amount of geomaganetic data, satellite data and other earth space observation data for power grid storm disaster monitoring.

A comparative analysis of the related works on Cloud storage on the basis of structure is given in Table 7.

4.3.4. Data management

Researchers have widely used existing Cloud services to effectively handle and manage the data in their systems while some have developed their own data management framework to better suit their purposes. Ji et al.[105] deployed Hadoop for effectively handling and processing the Geospatial data in their Geospatial workflow application maintained over a Cloud environment. Chavan et al.[115] used basic spatial operators, computational geometry operators and Open Geospatial Consortium compliant operators for handling the user queries under an optimized plan given by Query Optimizer in the system that worked on based on a cost model. Grolinger et al.[94] used proprietary graph query language called Cypher to query the data stored in graph databases maintained within a Cloud environment. Ramachandran et al.[114] developed CUMULUS as a native data management system which generated granule-level metadata with collection-level metadata stored in the catalog pointing to the storage locations maintained over AWS Cloud environment. The system used Amazon Lambda, EC2, EC3, S3 and SQS services for data processing. Wang et al.[111] proposed a distributed data management services for storage, where the service kept track of metadata about spatial and computational features of every data set and results were fetched based on the requirements of the queries. The effective handling of the flood data was ensured using Google Fusion Table where additional location information was presented as MultiGeometry using Keyhole Markup Language (KML). The queries were similar to SQL queries and data was updated in the table only after satisfying some predefined criteria. The Knowledge as a Service (KaaS) model proposed by Grolinger et al.[116] used a series of steps such as text extraction from images, file metadata separation, pattern processing and tagging for effective data management. The database for various environmental aspects data maintained by Montgomery et al.[36] were automatically connected to external databases, internet sites and other different sources using standard protocols of SQL, HTTP and FTP. Jiang et al.[86] used HBase and MapReduce to store Attribute Data and process data, respectively, in their framework. The smart evacuation system built by Qiu et al.[98] used MapReduce functions to perform required data analysis over the data collected by different sensors installed all over the cities. Puthal et al.[60] explained the methods of batch processing and data stream processing for analysis of the data collected from known and unknown sources where they focused on data stream processing of the data over the Clouds for real-time event detection. The solution proposed by Bohm et al.[89] consisted of different data layers for various visualization methods such as clustering, heat-map and polygons. Search queries were made to be based on attribute rather than spatial ones in the marine life data system developed by Fujioka et al.[108]. The data servers maintained over the Clouds in Maas framework proposed by Li et al.[51] handled metadata management for all the output data produced after ensemble run of the models. Rossi et al.[65] used .NET Entity framework as Object Relation Mapper and REST architecture for querying the stored data. Miska and Kuwahara[112] focused on storage of data with meta information for better handling and management with better understanding of the data.

Kalabokidis et al.[38] used ArcGIS server to effectively handle the stored data in VirtualFire. Li et al.[90] used a distributed hash tables (DHTs) to locate desirable data and resolve any queries efficiently in a community based emergency management system. PipsCloud [110] used HBase as metadata depository for handling the metadata management and Google File System (GFS) for RS data management. Li et al.[35] used Cloud Computing technologies such as Bigtable and MapReduce along with spatial indexing to query high volume of FCD over the Clouds for effective monitoring. Schnase et al.[34] facilitated the support for metadata to identify the properties of stored object for easier management of the data archive maintained over the Clouds. Behzad et al.[37] used Geospatial middleware for effective data management in their work for ground water simulation.

4.4. Control Mechanism

Researchers have used different frameworks and techniques to enable various control functions within their systems to efficiently use the Cloud environment. Chavan et al.[115] proposed the technique of space-filing curves for load balancing across all the cores of GPU to enhance the performance of the system by utilizing all the processing units. The study done by Garg et al.[**?**] incorporated deadline-based execution, effective load balancing, on-demand execution, fault tolerance and scalability in the system so as to be able to handle multiple requests from the concurrent users. The Cloud-based simulator developed by Eriksson et al.[87] used Condor framework for job distribution and management of EC2 and local resources. Huang et al.[113] used Amazon SQS to handle the queue of the users in a reliable and scalable manner when user requests are traveling between computers. PipsCloud used xCAT to extend the capabilities of OpenStack for supporting resources provisioning. Vockler et al.[106] constructed a virtual Condor pool to handle the resource provisioning in the system proposed for running the application on astronomical data over the Clouds. The system used Pegasus, DAGMan and Condor for failure recovery mechanisms.

5. Future Directions

Cloud Computing has revolutionized the way computing is carried out in many fields, with its unprecedented benefits in scalability, computational resources and vast potential storage. Based on this literature survey, NDM is an excellent candidate for deployment on Cloud systems, but there are still factors within this discipline that make implementation on the Cloud non-trivial. The work carried out so far has shown the possibilities and benefits of integrating Cloud technologies with Disaster Management, such as the ability to offer end services to agencies and authorities, and even general public during emergency and natural disasters. This work can be extended to to fully utilize the capabilities of Cloud Computing and address the various challenges in the field. Liang et al.[117] called for the development of Cloud Computing applications for disaster monitoring, forecasting and warning to mitigate potential losses caused by the disasters. Bessis et al.[103] proposed a roadmap highlighting the possible use of new and emerging technologies to enable collective computational intelligence in managing disaster situations. These examples illustrate that the adoption of Cloud technologies in Disaster Management may significantly help in minimizing the impacts and losses from natural disasters.

As such, the following section discusses and analyzes potential research areas for the integration of Cloud Computing to NDM and highlights future directions where research can be focused for more effective disaster management.

5.1. Effective Handling of Ensemble Simulations

Geospatial processes and Natural Hazard models may require ensemble simulations to calculate probabilistic outputs based on uncertain input conditions. This involves running a set of simulations, where each simulation is usually based on a complex physical model. Computing a set of simulations requires a correspondingly larger computation time than a single simulation and, depending upon the complexity of the model and number of uncertain parameters, such ensembles may take anywhere from several hours to days to complete on servers or local workstations. Ensemble runs of the Geospatial model in different instances introduces further complications due to the necessity for ordering and synchronisation of results. Every output from every single run of simulation must be carefully collected, stored and processed for further reduction and statistical analysis steps.

A recent study carried out by De Luca et al.[109] used the Cloud Computing environment to perform unsupervised processing of large SAR data volumes on a large number of computing nodes in an Amazon Web Service environment. The study suggests Cloud Computing may be a possible alternative to HPC scheme for ensemble simulations of Geospatial processes. However, there is a current need to develop an optimized mechanism for distributed modes of operation for ensemble simulations in the Cloud. Neither this nor any other study have defined or considered any computing schema that considers time-sensitivity, resource utilization and user-defined requirements when it comes to implementation of an NDM model.

A future development pathway would be for an optimized mechanism for ensemble simulations ensuring maximum resource utilization within a user-defined cost or time envelope. This could involve the development of a robust and optimized mechanism for independent operation of simulations over a number of instances making sure any idle instance in the configuration could take over the other sets of simulations from other instances. Development of this mechanism would involve the use of different optimization techniques so as to ensure all the resources during the run are used in an effective and efficient way.

The concept of a centralized storage system would also be useful for ensemble simulations, but this must be a well-defined mechanism that pushes and pulls the results on demand from the storage system. Aggregation of results can be more challenging if these have to be filtered for an optimized visualization. The centralized storage system would have to deal with large amounts of data and may require an effective method to filter out any irrelevant results. A central storage system can also be important in caching any replicated ensemble runs of the model for the same set of parameters or inputs. Furthermore, the storage system could be coupled together with an effective checking algorithm as a pre-processing filter for unnecessary simulations in the ensemble, saving valuable computational time and resources.

5.2. Integrated Natural Hazard Models

As previously discussed, a natural hazard represents a significant risk to the environment, people and infrastructure. Any relevant information prior to and after the occurrence of the natural hazard can be crucial in minimizing the impact of the disaster. Such information can include historical information about the occurrence of a particular disaster in a specific area, prediction results for any disasters, information about the extent of impacts of the hazard for a particular location, disaster response management and damage assessment. Various studies have been carried out to provide such functionality in a Cloud environment but, so far, in an isolated manner. Furthermore, little has been advocated and addressed in the need for a complete disaster management system that is able to handle the spectrum of needs from preventive measures to post-disaster damage assessment.

Future Natural Hazard Management systems can leverage the capabilities offered by Cloud Computing. Such a system could use a data archive within the Cloud environment to provide instantaneous access to historical occurrences of disasters at a particular location of interest to better inform authorities or the general public for effective planning in case of an actual events. During an actual event, a disaster model can offer an end service to predict factors such as evacuation or impact times. This could allow individuals and agencies can take action within an available time window. Moreover, effective planning strategies could be developed using risk metrics based on ensemble runs of a natural hazard model. Furthermore, a disaster model could deliver a visualization platform on top of the Cloud environment to keep track of operational resources to effectively and optimally mobilize these during an actual event. Such a management system could also incorporate crowd-sourced real-time information of the disaster to form a clearer operational picture of the unfolding events.

Such a system could be based on an efficient group modules consisting of Geospatial processing and natural hazard modeling elements provided in a complete system. This complete system could be deployed over a Cloud environment and a generic framework for all natural hazards. Future development on such systems should be able to ensure seamless end services with clear and well-defined results to its users. Under this complete system, future research work could be directed to facilitate interoperability of different data storage techniques and more advanced capabilities enabled by evolving Internet of Things (IoT) applications. Some potential areas to focus on for such a system would be:

5.2.1. Handling the challenge of Big Data within Cloud

For disaster management, data from a wide range of sources are to be considered. This includes the real-time spatiotemporal data from location services, social media, volunteer geographic information, satellites and UAVs[118]. The data from sensor web and IoT, airborne and terrestrial Light Detection and Ranging(LiDAR), simulation, spatial data, crowdsourcing and call data records are shown to be important for disaster management in [119]. For an effective hazard model, a number of diverse data sets may have to be repeatedly processed and analyzed by different modules to derive useful results. Therefore, the lack of interoperability between different data types can significantly hinder performance and the effectiveness of any system if not properly addressed[120].

Given the large amount and sources of data, manual analysis and interpretation of such integrated data are to be replaced by sophisticated and advanced automatic mechanisms to make the data analysis more efficient and effective[119]. Different machine learning techniques (text classification in [121][122], Neural Networks in [123],[124], [125]) have been used to derive more accurate results for disaster response and assessment for different disasters. Moreover, studies[60],[54], [126] have emphasized in setting up big data cyberinfrastructure for disasters that can help in efficient data collection, information extraction, distribution and visualization for effective disaster management. Future works should look into challenges created by a cyberinfrastructure in relation to efficient data management, more intuitive data visualization and low latency during data transfer. Various studies have made use of a wide range of data storage techniques, but there are no clearly defined mechanisms that explain how heterogeneity in data storage can be effectively dealt with. Due to this, future work should focus on effective mechanisms to support the interoperability between heterogeneous data sets within the Cloud environment. There have to be efficient analytical methods that can integrate the crowdsourced data with Geospatial data for better disaster situation awareness and prediction.

5.2.2. Handling Inaccessibility of Cloud Services during the Disasters

During the actual occurrence of the disasters, as Cloud services may be inaccessible due to communication and power outages, fog/edge computing can play a significant role in the optimal mobilization of the emergency response teams. As highlighted in the work[127], the rescue personnel engaged in search and rescue operation can be continuously tracked using end devices like phones and sensors. This tracking enabled by fog computing can be used to create a real-time density map of people in the affected region that can help and guide the response teams. In edge computing, a varying degree of computational powers is available to end devices like cell phones, tablets, cameras and sensors. Thus, less compute intensive processing can be directed towards these end devices rather than the traditional cloud infrastructure to significantly decrease the latency[128]. Similarly, in crowdsourced data analytics, more sensitive data can be processed closer to where they are generated while other data can be sent to the Cloud for further historical analysis and storage[57]. The end devices in fog/edge computing can make the people and the responders situationally aware for better-informed decisions during the emergencies[57]. Thus, there is no doubt that a Cloud-based solution can be used in conjunction with end-devices of fog/edge computing and IoT networkby distributing the services based on time-sensitivity and compute-intensiveness. Use of IoT sensors could facilitate greater readiness and responsiveness but bring further challenges of *Big Data* within a Cloud-based system. Although there has been significant work carried out in addressing the challenges of handling massive data sets collected by extensive

IoT sensor network in general[129],[130],[131], there are no clearly defined capabilities for scalably handling and processing such Geospatial data streams. Furthermore, there are not clearly defined architecture to integrate the evolving paradigms of edge and fog computing within a Cloud-based solution for effective diaster management. Future research could center around better integration of IoT sensor networks, Edge and Fog Computing in Disaster Management for more advanced real-time services.

5.3. Addressing the need for concurrent access and dynamic configuration

This work has highlighted the need for intensive ensemble simulations for Geospatial processing and natural hazard models, ideally offered as an end service. Examples have been given of migration of some models to a Cloud infrastructure from the traditional use of a local HPC scheme with a set of static configuration. Ensemble simulations for such models are governed by a set of user inputs and a Cloud-based system must be able to update and change an entire set of Geospatial process if any of these inputs are changed without compromising performance. Moreover, it is not just a single user that may be using the model at a given instant of time, and any end service must be able to be concurrently accessed by a multiple users at different locations. There is a significant need for future systems that can effectively handle multiple sets of ensemble simulations with different configurations and concurrently provide results to a wide number of users. Future effective general-purpose systems must address these issues of concurrent access and dynamic configuration for ensemble simulations. This could result in improvements in existing resource pooling, scheduling, queuing and load balancing techniques for the advanced and sophisticated algorithms required to effectively deliver disaster management systems on the Cloud.

5.4. Overcoming the bottleneck of Network Capabilities

Ensemble simulations for disaster management models within the Cloud environment are by nature intensive in concurrent-access, data processing and computation. The processing of huge data sets requires a large amount of data to be transferred between nodes in the Cloud. However, Cloud infrastructure may have limited network capacity that could potentially create bottlenecks in the development of Cloud based natural hazard modeling systems. Given the migration of disaster management models to the Cloud and the growing data intensiveness of such models there may be future performance and scalability issues owing to the large number of interacting services and networks. This requires effective network management services to ensure seamless integration and delivery of data-intensive Geospatial processes based on Cloud Infrastructure. Future work to address this could include automation of specific network functions in the Cloud environment to keep up with networking demands of the Geospatial processes. A possible separation of the control plane from the data forwarding plane in Software Defined Networks(SDN)[132] could be studied to find newer ways to accommodate and adapt to dynamic workload and find an optimized configuration for ensemble simulations. Moreover, future works could focus in exploring and discovering new ways of utilizing networking hardware to realize the full potential of massively distributed Cloud computation.

6. Conclusion

The increased sophistication of modeling natural processes, improvement in data collection technology and advancement of web services has led to Geospatial models becoming increasingly intensive in computation, data processing and requirement for concurrent-access. The traditional foundation of ICT cannot effectively support the offering of Geospatial models such as NDM tools as a service. Cloud Computing is an attractive platform to address these challenges with almost unlimited capacity of for scalable computation, storage and networking. As covered in this survey, there are a wide variety of models and processing technologies that address various aspects of Disaster Management. These models and technologies are gradually being migrated into the Cloud for better flexibility, scalability, access and performance. We have identified commonality between these various systems and proposed a generic framework for offering the functionalities of hazard models as a service. The huge dependency of Cloud services on internet connectivity and regular power supply can make these services inaccessible during the disasters due to the breakdown of communication and electricity infrastructure but Cloud infrastructure still remains an inseparable entity to support data and compute-intensive modeling and simulations of natural disasters. To overcome the vulnerability of Cloud services during the disasters, we have extended Cloud Computing in the proposed framework to include evolving technologies such as IoT network, fog and edge computing, which can offer some critical disaster-related services and act as a transitional data relay for further assessment in Cloud. We have also identified trends in research and identified future research areas which we believe will be important for this area for newer and more advanced capabilities of disaster management. Next generations of NDM systems can employ integrated Geospatial intelligence systems, ingesting real-time Remote Sensing and spatial data feeds, in combination with advanced modeling and visualisation technologies deployed over the web. Such systems can only be deployed using the power and scalability of the Cloud, together with evolving technologies like IoT network, fog and edge computing.

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