Reports on Geodesy and Geoinformatics, 2025, Vol. 119, pp. 7–13

DOI: 10.2478/rgg-2025-0002
Received: 24 October 2024 / Accepted: 2 January 2025
Published online: 24 January 2025

ORIGINAL ARTICLE

Real-time geo-decisional system for risk and disaster management in Madagascar

Tsiorinantenaina René Rakotoarison [1,2*] and Aimé Richard Hajalalaina [1,2]

[1]School of Management and Technological Innovation, University of Fianarantsoa, Andrainjato, Fianarantsoa, zip code 301, Madagascar
[2]Laboratory of Computer Science, Geomatics, Mathematics and Applications, University of Fianarantsoa, Andrainjato, Fianarantsoa, zip code 301, Madagascar

[*]rtsiorinantenaina@gmail.com

Abstract

Climate change is intensifying extreme phenomena, and the world is increasingly vulnerable to a variety of disasters whose impacts are considerable and varied over time, from one place to another and from one community to another. Due to its geographical location, Madagascar is the most cyclone-prone country in Africa and the ninth most vulnerable country in the world. Almost every year, Madagascar is hit by cyclones, causing loss of life and property for the population. In terms of prevention, Madagascar already has an early warning system to inform the population, but during a crisis, it still lacks a decision support system for rapid, real-time intervention to minimize damage. In this paper, we propose a real-time geo-decision support system based on real-time data integration, real-time ETL and real-time cube building. In the proposed architecture, continuous data flow is required for real-time data integration. The proposed real-time ETL unit is composed of the capitalization of risk analysis experiments to ensure their reusability, as well as the insertion of processing parallelization to optimize the processing time of voluminous data. The real-time SOLAP unit consists of real-time cube formation using a spatial database that stores spatio-temporal data from a given point in time, with query optimization using materialized query technology. Our prototype uses NASA's weather data streaming service via an API. The ETL is written in a Matlab script and loads the data into a spatial database in Postgresql after processing. A web mapping application queries the constitution of a cube and displays the result for visualization.

Key words: Geo-decisional, real-time, risk, disaster, Madagascar

1 Introduction and context

Madagascar is highly exposed to risks from a number of hazards such as cyclone, flood and drought due to its geographical position (Nematchoua et al., 2018). It is ranked as the most cyclone-prone country in Africa. Madagascar is regularly hit by tropical cyclones during the cyclone season, which generally runs from November to April. These cyclones can cause high winds, torrential rains, flooding and landslides, resulting in loss of life, displacement of populations and significant material damage (Weiskopf et al., 2021). Heavy rainfall, often associated with cyclones, as well as heavy rains during the rainy season, can cause widespread flooding. Flooding can damage infrastructure, destroy crops, cause water-borne diseases and lead to massive population displacement. Some regions of Madagascar face periods of drought, which can lead to water shortages, food crises and economic hardship. Communities dependent on agriculture are particularly hard hit, and food security becomes a major concern during these periods. During Cyclone Batsirai's passage through Madagascar on February 2022, the Bureau national de gestion des risques et des catastrophes (BNGRC), in its latest provisional assessment

Publisher: De Gruyter

published on February 10, 2022, counted 112,000 victims from 23,444 households, more than 61,000 displaced persons, more than 7,400 dwelling huts destroyed and more than 2,700 others damaged (Mandimbisoa, 2024). The Malagasy government, with the support of national and international organizations, is implementing risk and disaster management measures. These include strengthening emergency response capacities, improving resilient infrastructure, developing early warning systems, raising awareness among local populations and coordinating efforts between different stakeholders. However, the system for decision-making and real-time intervention is still unsatisfactory, and is increasingly amplifying the damage. Risk management and the monitoring of natural phenomena often require real-time information for rapid and effective decision-making by the various stakeholders (Gutiérrez and Servigne, 2007). Rapid and timely intervention by decision-makers can reduce disasters such as loss of life and property, and the destruction of infrastructure. Information useful for risk management, such as meteorological data, seismic data and information from environmental sensors, exists with real-time accuracy and availability (Nguemdjo, 2023), but integrating, transforming and analyzing this diverse data in real time represents a complex challenge. The main issues addressed in this paper are the integration of heterogeneous spatial data in real time, the latency of Extract, Transform and Load (ETL) execution with complex extraction, transformation and loading algorithms, and the real-time cube building towards visualization.

2 Related work

The real-time geo-decisional system for environmental monitoring from Resch et al. (2009) makes extensive use of open geospatial standards throughout the integration of sensor data, the analysis process chain and finally visualization. Real-time geo-decision systems require a continuous flow of sensor data. Mathieu (2011) has proposed an approach for integrating real-time sensor data into a geo-decisional data warehouse. This approach relies on the publication and standardization of sensor data based on the standardized syndication SensorGeoRSS. The work of Kissi et al. (2008) on the integration of heterogeneous data for an environmental decision support system (DSS) is based on the way in which data are acquired and made available. Their fields of application focus on continuous natural or anthropogenic phenomena with spatial and spatial-temporal data. This work proposes to DSS architects a concept for building the appropriate system by evoking the complete processing chain from data acquisition to data availability for decision analysis. Data from the various sensors is current data, and can be coupled with archived data for decision analysis. The sensor observation stage complies with the SWE (Sensor Web Enablement), a standard of the Open Geospatial Consortium (OGC) (Reed et al., 2007). It provides standard data as specified in ISO 19123 (ISO, 2005). The data collected is then transformed into continuous data for use as current data and will be introduced into the DSS system according to the ISO 19123 standard on coverage. SensorGeoRSS is a GeoRSS-based format that is simple and light to implement for applications. It requires real-time dissemination of geolocated information, but is less flexible than SWE in terms of sensor description and data manipulation. The work by Bimonte et al. (2006) proposes a web-based SOLAP (Spatial Online Analytical Processing) system with the aim of resolving problems concerning aggregation operations and cube navigation in semantic and implementation aspects. The architecture is composed of three levels: a relational DBMS that supports geographic data, an OLAP (Online Analytical Processing) server, an OLAP web client and a GIS web client. Together with the RDBMS, they support the complex aggregation of a SOLAP by creating their own PL/SQL aggregation function in ORACLE. Boulekrouche et al. (2016) integrate in their work the task of spatial ETL in a distributed and parallel way by the grid computing technique in order to manage to update the spatial data warehouse in acceptable delays given the increasing volumes of spatial data. To ensure the automation and reusability of ETL processing, Hajalalaina et al. (2017) proposes the construction of the knowledge base based on existing standards in terms of interoperability, whether data or processing. The real-time decision support system for space mission control by Pires et al. (2004) proposes two databases: the real-time database, which is updated daily with data from external sources for real-time analysis, and the data warehouse, which contains forecast data. Lambert (2006) developed an approach to real-time SOLAP analysis in top-level sport. Their work consists of verifying that the SOLAP analysis used in business can be transported into athlete performance analysis, as coaches are keen to obtain timely data on current athlete performance. This work proposes five SOLAP categories according to response time and frequency of new data entry. To optimize the time constraint, they proposed to materialize repetitive and time-consuming aggregation calculations.

3 Real-time geo-decisional system

A real-time geo-decisional system is a decision support system that uses continuously updated spatial data to help decision-makers take decisions based on spatial information. The system is characterized by:

- the integration of spatial data from different sources including sensors, data providers and spatial databases;
- real-time ETL based on the capitalization of expert processing chains and the optimization of processing to ensure the time constraint of the real-time system;
- real-time SOLAP analysis by materializing spatial queries to improve performance with the process of physically storing query results in a table, rather than recalculating these results with each query execution;
- real-time SOLAP analysis by materializing spatial queries to improve performance with the process of physically storing query results in a table, rather than recalculating these results with each query execution.

3.1 Data integration

Typically, the data sources that feed the real-time geo-decision-making system are categorized into three, such as the network of sensors for observing current data on environmental phenomena, suppliers of climate data and existing data archives in spatial databases which is shown in Figure 1.

The sensors are used to observe continuous phenomena that vary in time and space, in accordance with the OGC standards of the SWE initiative. They can be used to acquire standard topical data in accordance with ISO 19123 (Kissi et al., 2008). Continuous data integration accesses near-real-time data from data centers (ECMWF, NASA, NCAR, etc.). The collaboration of W3C (World Wide Web Consortium) and OGC since 2014, which aims to improve the interoperability and integration of spatial data on the web, has a willingness to consider the web of data right from the specifications towards a more RESTful approach providing data in standard formats such as JSON (Grellet, 2019). Most providers of this data have already designed web service technology based on W3C recommendations, using APIs and OGC standards. Data acquisition from existing spatial databases is based on ISO 19142, a standard that defines the Web Feature Service (WFS) for accessing spatial data in the

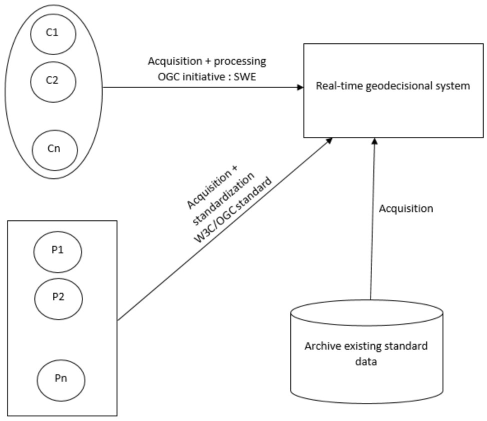

Figure 1. Data source

form of "features" (geographic objects), which are generally represented by points, lines or polygons with attributes. In addition to retrieving spatial data, it can also be queried, updated, inserted and deleted. There's also the Web Coverage Service (WCS), an OGC standard for accessing coverage data (such as raster images or data grids). Unlike Web Map Service (WMS), which generates maps in the form of images, WCS enables raw data to be downloaded in the form of coverages, which is useful for geospatial analysis.

3.2 ETL based on experience capitalization

Spatial ETL, also known as geospatial ETL, is a process used in the field of geoinformatics to collect spatial data from different sources, transform them into a consistent format and load them into a spatial data warehouse for subsequent analysis. In our case study, the transformation involves processing the extracted data for risk analysis. A great deal of experience has been gained in spatial data processing in the field of risk management and natural disasters, but this is still compartmentalized within the laboratories or research centers that design them. The aim is to set up a knowledge base to store the experimental processing chains. ETL modelling must include conceptual, logical and physical process models (Astriani and Trisminingsih, 2016). The workflow system process of Libourel et al. (2010) enhances the semantic presentation of experiments by passing through the stages of planning, instantiation and execution based on the metamodel of the work context (Hajalalaina et al., 2017). Planning defines the expected processing chain in an abstract way, instantiation consists in identifying the elements needed to carry out the processing chain, and execution calls on the actual resource available. We adopted multicriteria analysis in our experimentation, which is a mathematical method to help decision-makers faced with a complex problem dependent on several criteria of a qualitative or quantitative nature (Navalho et al., 2019). Data for spatial analysis are complex, heterogeneous and non-linear (Chakhar, 2006). However, the Analytical Hierarchy Process (AHP) method by Saaty (1980, 1990) has been proposed because of its simplicity at the computational level, which allows it to be easily explained to a decision-maker. The problem is decomposed into several levels to transform the data into a form of degree of risk and vulnerability (Rakotoarison et al., 2021).

3.3 ETL processing time optimization

Spatial data processing requires enormous resource capacity, as spatial data are voluminous, complex and heterogeneous. This leads to latency in the ETL process, which does not feed back into the system in real time. In order to cope with the above-mentioned limitations and requirements, parallel processing techniques on distributed environments are relevant solutions for achieving real-time spatial ETL. Recent approaches rely instead on open source tools, such as the Map Reduce framework, cluster, grid computing and cloud computing, which are cheaper and faster solutions than expensive proprietary ETL tools (Misra et al., 2013). Our approach combines the workflow notion of processing chain planning and instantiation with the runtime technique in a parallel and distributed programming model to ensure acceptable time and high availability of real-time spatial ETL.

3.4 Real-time SOLAP

Real-time SOLAP (SOLAP TR) is a reactive system in which the warehouse is refreshed and the cubes reconstituted immediately following the acquisition of new data. The constraint on SOLAP TR is the time required to calculate aggregations on new entries in the EDS. To meet the minimum response time to customer queries, frequent and heavy queries need to be materialized, whereby the results of a query are pre-computed and physically stored in a separate table, allowing quick access to pre-computed results without having to execute the underlying query each time (Date, 2011; Hung et al., 2004; Kimball and Caserta, 2004). However, materialized queries need to be kept up to date. It is necessary to refresh the materialized query as soon as the data changes to ensure that the results remain up-to-date (Jogekar and Mohod, 2013). Lambert (2006) has indicated five (5) SOLAP categories according to their response times and the frequency of warehouse refreshes and the reconstruction of SOLAP analysis cubes:

- Real-time SOLAP, which provides accurate responses within the time constraint (<0.5 sec.);
- SOLAP Quasi-Real Time, which also provides accurate answers, but may not respect the time constraint (0.5 sec.) at certain times;
- SOLAP propitious time, where the warehouse is refreshed several times a day, for example hourly;
- SOLAP just-in-time, in which the warehouse is refreshed and the cube reconstructed at the user's request;
- SOLAP Traditional.

4 Architecture proposal

Risk and vulnerability analysis is based on several factors such as climatic, geographical and socio-economic factors (Rakotoarison et al., 2021). Data sources can be categorized according to their update frequency. Climatic factors are rather dynamic sources with real-time data flow, while geographical and socio-economic variables are hosted from sources with low update frequency. Data come from a variety of sources, including weather sensors, climate data providers and existing spatial databases. For sensors, the OGC SWE initiative specifies data access and standardization (Kissi et al., 2008). Climate data providers offer access via the W3C web service standard (Grellet, 2019) and data are transformed in accordance with the OGC data standard. Data in existing spatial databases can be accessed via OGC services (WCS, WFS, WMS). Real-time processing requires a more active ETL process with minimal delay (Salem, 2012). Given the heavy volume of spatial data, we propose the approach of distributing and parallelizing processing to optimize process execution time towards real-time ETL (Boulekrouche et al., 2016). We therefore propose the creation of an experience base to ensure the automation and reusability

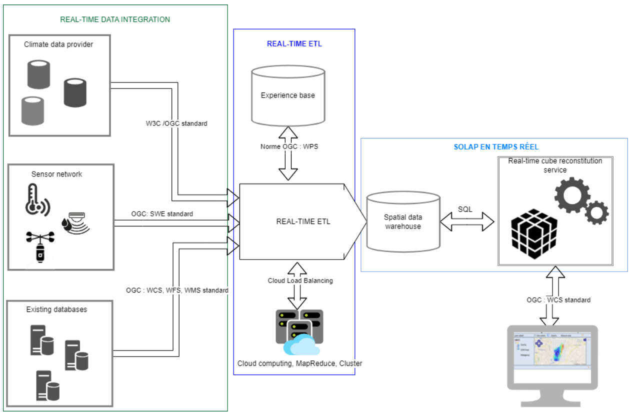

Figure 2. Architecture proposal

of ETL processing chains (Hajalalaina et al., 2017). The data warehouse is a real-time database that is rather different from the characteristic of the classic data warehouse, as it stores recent data in real time and is volatile (Pires et al., 2004). Real-time SOLAP is based on building the cube in real time, optimizing queries with materialized view techniques (Date, 2011) and transmitting results to geo-visualization via web technology (Bimonte et al., 2006). The architecture is shown in Figure 2.

5 Real-time geo-decisional system for natural hazard and disaster management

5.1 ETL based on the multicriteria analysis method

ETL is the process of integrating and transforming data from different sources (Shekhar and Xiong, 2007). In the case of our system, it extracts real-time climate data from data providers via available web services, geographic data in existing databases such as elevation and slope to identify flood risk areas, and data on socio-economic issues to identify vulnerability. The transformation part is based on multicriteria analysis (MCA), which is a science and technique for clarifying the understanding of a complex decision problem (Navalho et al., 2019). Decision-making is frequently multi-parameter or multi-criteria dependent. Spatially-referenced decision problems are multi-criteria in nature, hence several papers integrating spatial and multi-criteria analysis have been published since 1990. The problem with spatial analysis is that the data are complex, as existing geographic features and phenomena are characterized by their position, shape, descriptive attributes, topological relationships and formats, depending on their source, and the area to be analyzed is continuous or the number of possibilities is very high, e.g., all the pixels of the map (Chakhar, 2006). We proposed the hierarchical analysis process (AHP) of Saaty (1980), because with some methods, the calculation time becomes very long. We took the major hazards in Madagascar, cyclones and floods, which occur in the country almost every year, and decomposed the problems into several levels, as shown in Figure 3 and 4.

A weighted linear combination is applied to the different level 2 and level 1 factors of the analysis hierarchy (Deepak et al., 2020) according to the equation:

$$S = \sum w_i \cdot x_i \tag{1}$$

Hence: x_i – value of normalized factors; w_i – estimated weight of each factor; S – score or linear combination of factor values (x_i) weighted by weights (w_i).

The different factors are rarely expressed in the same unit. To be able to combine factors, it is necessary to normalize them using reduced centered variables.

$$x_i = \frac{f_i - \bar{f}}{\sigma f} \tag{2}$$

Hence: f_i – factor values; $\bar{f}$ – average of factors; σf – standard deviation.

5.2 Data warehouse for hazard vulnerability

Figure 5 shows the model representing the schema of the spatial data warehouse with a “Vulnerability” fact table that has a “Vulnerability value” measure, with the value of the degree of vulnerability according to the type of hazard. The spatial dimension is presented by the “Location Point” table, which locates a point position of a vulnerability value. This point belongs to a district, and several districts make up a region. The other two classic dimensions are time and hazard type.

5.3 Prototype implementation

NASA’s POWER API is used for reproducible data retrieval (Sparks, 2018). In this prototype, we retrieved data via http requests to the NASA-POWER system API (https://power.larc.nasa.gov), which was designed to provide weather information directly usable in an architecture (Stackhouse Jr et al., 2015). This system integrates data from different sources such as real-time daily data for air temperature and relative humidity, which are obtained from the Global Office of Modeling and Assimilation system (GEOS-4), and precipitation data, which are obtained from the Global Precipitation Climate Project (Júnior et al., 2019). In the ETL part, we extracted the data from the API in a Matlab script. In terms of transformation, our previous work proposes a processing chain written in Matlab script for risk and vulnerability analysis using the AHP method (Rakotoarison et al., 2021). We reused this experimental database before loading the results into the real-time database. A spatial database is designed in PostgreSQL with the PostGIS extension to store real-time results. Webmapping is used for visualization, using the mapserver as a map server with the Geomouse framework. Figure 6 illustrates this software architecture and Figure 7 shows the result geo-visualization interface.

The client makes a request to the webmapping application with temporal and spatial parameters. The application queries the database, and if the requested query does not yet exist, the application calls on the ETL processing server to extract the new data via the Power NASA API and process it before depositing it in the data warehouse. The map server interfaces the database with the map display.

6 Discussion

In emergency situations, partial results obtained in time are more important than complete results obtained later (Bouzefrane et al., 2008). This context shows the interest of our real-time geo-decisional system. The components of this real-time geo-decisional system are real-time data integration, respecting standards on access to data from different sources; real-time ETL, which brings together experiment management and processing time optimization with cloud computing parallel processing techniques; and real-time cube building, optimizing queries. The advantage of this real-time system is its enhanced reactivity, enabling us to react to critical events such as natural disasters. A performance analysis is required to assess

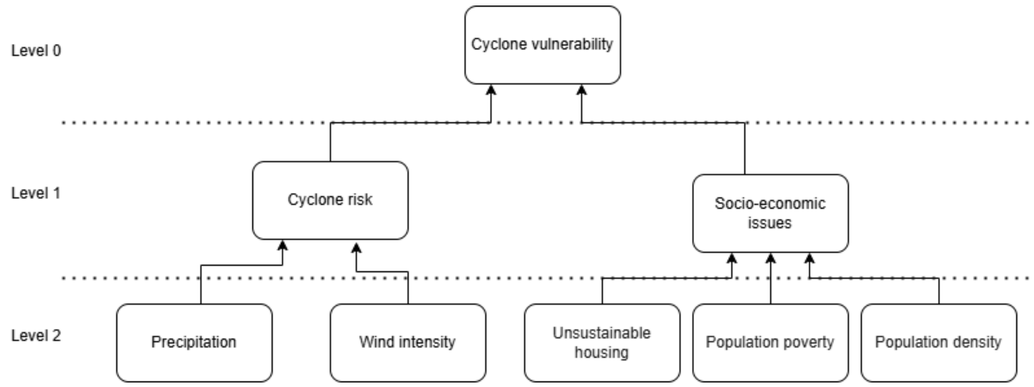

Figure 3. Hierarchical analysis process for cyclone vulnerability

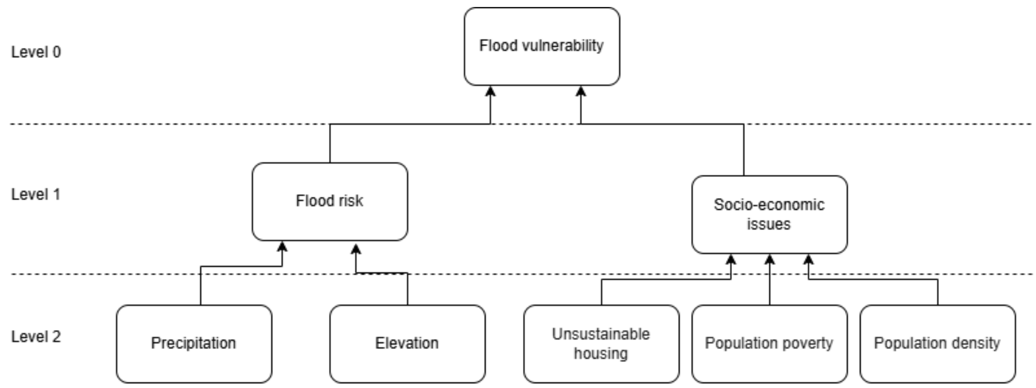

Figure 4. Hierarchical analysis process for flood vulnerability

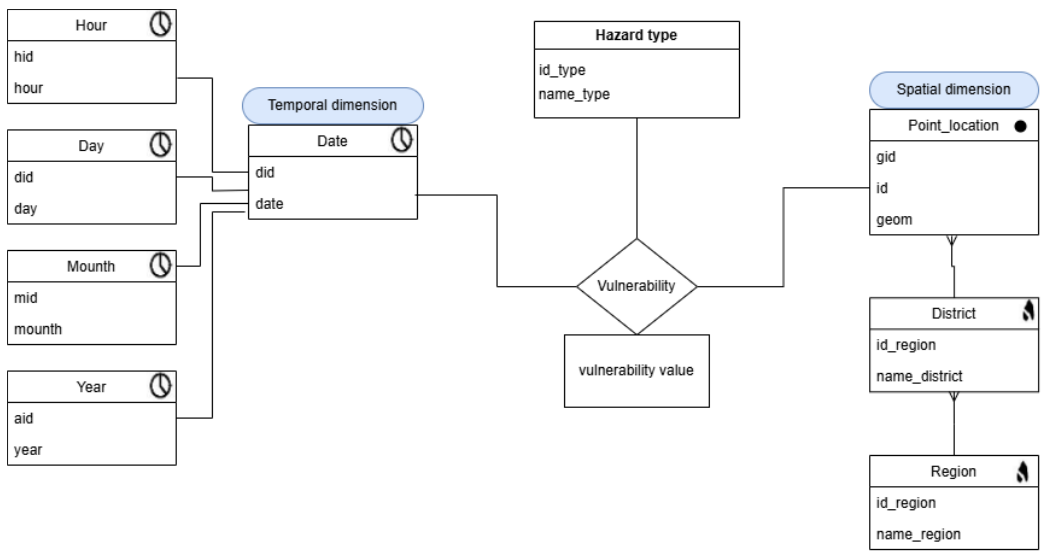

Figure 5. Schema of the hazard vulnerability data warehouse

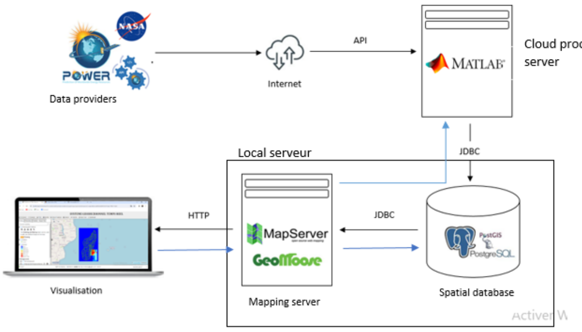

Figure 6. Prototype

the acceptable delay for this real-time system. In this architecture, calculated results are stored in a temporary real-time database. On the other hand, the prevention part of the risk management cycle requires archived results. This brings us back to the perspective of a hybrid system. Indeed, the temporary results in the real-time database will be fed directly into a conventional data warehouse (Pires et al., 2004). Another limitation of this system is that the results cannot be shared and exploited on the geo-visualization system we have proposed. This gives us food for thought about extending the architecture to include the notion of spatial data infrastructure. This approach requires the notion of spatial data metadata standards (Moumen et al., 2014; Noucher, 2006; Noucher and Archias, 2007; Rey-Valette et al., 2022).

7 Conclusion

This article is a contribution to the study of real-time geo-decisional systems. Our scope of application refers to the context of risk and disaster management in Madagascar. Timely decision-making can minimize the damage caused by natural disasters. We have proposed a suitable architecture for risk and disaster analysis based on loading real-time climate data and dynamic data on geographical and socio-economic factors into a real-time database. For the optimization of ETL execution times, we have proposed the parallelization and process distribution approach, as well as the experience base for the automation and reuse of ETL processing chains. In this architecture, we also propose real-time cube constitution via SQL aggregation functions and direct display of real-time results in webmapping. Prospects for improving the architecture have been initiated, such as the extension to a hybrid architecture involving the insertion of a conventional data warehouse to store the computed results in the real-time database, and also the inclusion of a spatial data infrastructure to ensure the sharing and exploitation of the results.

References

Astriani, W. and Trisminingsih, R. (2016). Extraction, Transformation, and Loading (ETL) module for hotspot spatial data warehouse using geokettle. *Procedia Environmental Sciences*, 33:626–634, doi:10.1016/j.proenv.2016.03.117.

Bimonte, S., Wehrle, P., Tchounikine, A., and Miquel, M. (2006). Gewolap: A web based spatial olap proposal. In *On the Move to Meaningful Internet Systems 2006: OTM 2006 Workshops: OTM Confederated International Workshops and Posters, AWeSOMe, CAMS, COMINF, IS, KSinBIT, MIOS-CIAO, MONET, OnToContent, ORM, PerSys, OTM Academy Doctoral Consortium, RDDS, SWWS, and SeBGIS 2006, Montpellier, France, October 29-November 3, 2006. Proceedings, Part II*, pages 1596–1605. Springer, doi:10.1007/11915072_66.

Boulekrouche, B., Jabeur, N., and Alimazighi, Z. (2016). Toward integrating grid and cloud-based concepts for an enhanced deployment of spatial data warehouses in cyber-physical system applications. *Journal of Ambient Intelligence and Humanized Computing*, 7(4):475–487, doi:10.1007/s12652-016-0376-1.

Bouzefrane, S., Etienne, J.-P., and Kaiser, C. (2008). Gestion de la surcharge dans les systèmes de gestion de base de données temps réel (Managing overload in real-time database management systems). *Tech. Sci. Informatiques*, 27(7):879–910.

Chakhar, S. (2006). *Cartographie décisionnelle multicritère : Formalisation et implémentation informatique (Multi-criteria decision-making mapping: Formalization and IT implementation)*. PhD thesis, Université Paris Dauphine – Paris IX.

Date, C. J. (2011). *SQL and Relational Theory: How to Write Accurate SQL Code*. O'Reilly Media, Inc.

Deepak, S., Rajan, G., and Jairaj, P. G. (2020). Geospatial approach for assessment of vulnerability to flood in local self governments. *Geoenvironmental Disasters*, 7(1):35, doi:10.1186/s40677-020-00172-w.

Grellet, S. (2019). Plateformes de données nouvelles API OGC et LINKED DATA (new data platforms OGC API and LINKED DATA). In *AfiGeo: Réunion Du GT Open Data – 13 Mai 2019*.

Gutiérrez, C. and Servigne, S. (2007). Métadonnées spatiotemporelles temps réel (Real-time spatiotemporal data models). *Ingenierie des systemes d information*, 12(2):97.

Hajalalaina, A. R., Raherinirina, A., Ratiarison, A., and Libourel, T. (2017). Modeling process chain of meteorological reanalysis precipitation data using work context. *International Journal of Information Technology, Modeling and Computing (IJITMC) Vol*, 5.

Hung, S.-L., W.-S., Li Yang, S.-Y., and Hsu, M.-C (2004). Maintenance of materialized views in data warehouse systems. *Journal of Information Science and Engineering*, pages 879–890.

ISO (2005). ISO-TC211 - 19123 - information géographique.

Jogekar, R. N. and Mohod, A. (2013). Design and implementation of algorithms for materialized view selection and maintenance in data warehousing environment. *International Journal of Emerging Technology and Advanced Engineering*, 3(9):134–140.

Júnior, W. M., Valeriano, T. T. B., and de Souza Rolim, G. (2019). EVAPO: A smartphone application to estimate potential evapotranspiration using cloud gridded meteorological data from NASA-POWER system. *Computers and Electronics in Agriculture*, 156:187–192, doi:10.1016/j.compag.2018.10.032.

Kimball, R. and Caserta, J. (2004). *The Data Warehouse ETL Toolkit*. John Wiley & Sons.

Kissi, R., Desconnets, J.-C., and Libourel, T. (2008). Intégration de données hétérogènes pour un Système d'Aide à la Décision environnemental (Integration of heterogeneous data for an environmental decision support system). *Atelier SIDE – INFORSID*.

Lambert, M. (2006). *Développement d'une Approche Pour l'analyse Solap En Temps Réel: Adapatation Aux Besoins Des Activités Sportives En Plein Air (Development of an Approach for Real-Time Solap Analysis: Adaptation to the Needs of Outdoor Sports Activities)*. PhD thesis, Université Laval.

Libourel, T., Lin, Y., Mougenot, I., Pierkot, C., and Desconnets, J.-C. (2010). A Platform Dedicated to Share and Mutualize Environmental Applications. In *ICEIS (1)*, pages 50–57.

Mandimbisoa, R. (2024). Plus de 112 000 sinistrés, selon le BNGRC.

Mathieu, J. (2011). *Intégration de Données Temps-Réel Issues de Capteurs Dans Un Entrepôt de Données Géo-Décisionnel (Real-Time Data Integration from Sensors into a Geo-Decisional Data*

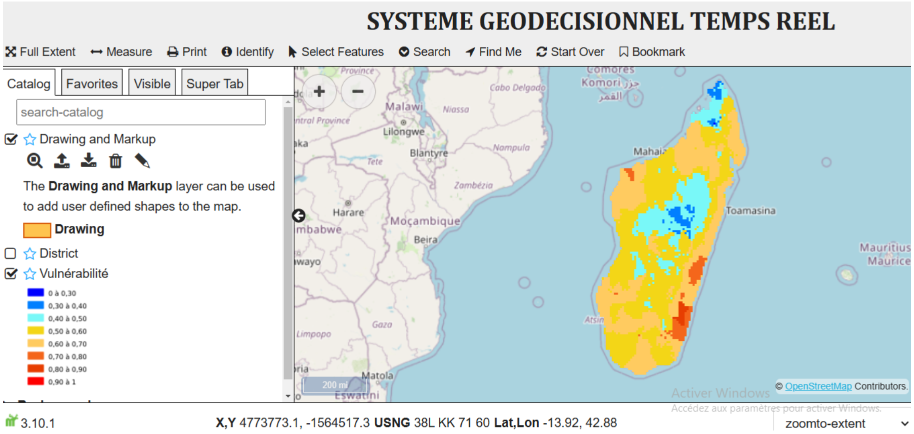

Figure 7. Visualization

Warehouse). PhD thesis, Université Laval.

Misra, Dixit, V, and Bhatnagar, R. (2013). Data analysis using open source tools: A comparison with ETL tools. *Journal of Computer Science and Engineering*, pages 123–130.

Moumen, A., Oulidi, H. J., El Mansouri, B., Nehmadou, M., and Khazaz, L. (2014). Géo-cataloguer les données sur les ressources en eau, un défi à relever. Vers une infrastructure de données spatiales de l'eau au Maroc (geo-catalogizing water resources data, a challenge to be addressed. Towards a spatial water data infrastructure in Morocco). *Revue Internationale de Geomatique*, 24(4):411.

Navalho, I., Alegria, C., Roque, N., Quinta-Nova, L., Navalho, I., Alegria, C., Roque, N., and Quinta-Nova, L. (2019). Mapping forest landscape multifunctionality using multicriteria spatial analysis. *Floresta e Ambiente*, 26(2), doi:10.1590/2179-8087.070217.

Nematchoua, M. K., Ricciardi, P., Orosa, J. A., and Buratti, C. (2018). A detailed study of climate change and some vulnerabilities in Indian Ocean: A case of Madagascar island. *Sustainable cities and society*, 41:886–898, doi:10.1016/j.scs.2018.05.040.

Nguemdjo, U. (2023). Les enjeux liés aux données climatiques (Issues related to climate data). Technical report.

Noucher, M. (2006). Mutualisation de l'information géographique-Communautés De Pratique Ou Infrastructures de Données Spatiales? (Sharing geographic information – Communities of practice or spatial data infrastructures?). Technical report.

Noucher, M. and Archias, C. (2007). Evaluation des infrastructures de données spatiales: Application d'une typologie au CRIGE PACA (Evaluation of spatial data infrastructures: Application of a typology to CRIGE PACA). Technical report.

Pires, J. M., Pantoquilho, M., and Viana, N. (2004). Real-Time Decision Support System for Space Missions Control. In *IKE*, pages 152–160.

Rakotoarison, T. R., Hajalalaina, A. R., Raonivelo, A., Raherinirina, A., and Zojaona, R. T. (2021). Spatial Analysis of Risks and Vulnerabilities to Major Hazards in Madagascar Using the Multi-Criteria Method Based on the Analytical Hierarchy Process (AHP). *Journal of Geoscience and Environment Protection*, 9(5):15–24.

Reed, C., Botts, M., Davidson, J., and Percivall, G. (2007). Ogc sensor web enablement: Overview and high level architecture. *2007 IEEE Autotestcon*, pages 372–380.

Resch, B., Mittlboeck, M., Girardin, F., Britter, R., and Ratti, C. (2009). Real-time Geo-awareness – Sensor Data Integration for Environmental Monitoring in the City. In *2009 International Conference on Advanced Geographic Information Systems & Web Services*, pages 92–97. IEEE.

Rey-Valette, H., Jabbour, C., Maurel, P., and Salles, J.-M. (2022). *Infrastructures de Données Spatiales: Évaluations Économiques: Concepts, Méthodes et Retours d'expérience (Spatial Data Infrastructures: Economic Assessments: Concepts, Methods and Feedback)*. éditions Quae.

Saaty, T. L. (1980). The analytical hierarchy process, planning, priority. *Resource allocation. RWS publications, USA*.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1):9–26, doi:10.1016/0377-2217(90)90057-I.

Salem, R. (2012). *Active XML Data Warehouses for Intelligent, Online Decision Support*. PhD thesis, Lyon 2.

Shekhar, S. and Xiong, H. (2007). *Encyclopedia of GIS*. Springer Science & Business Media.

Sparks, A. (2018). Nasapower: A NASA POWER Global Meteorology, Surface Solar Energy and Climatology Data Client for R. *Journal of Open Source Software*, 3(30):1035, doi:10.21105/joss.01035.

Stackhouse Jr, P. W., Chandler, W. S., Hoell, J. M., Westberg, D., and Zhang, T. (2015). An Assessment of Actual and Potential Building Climate Zone Change and Variability from the Last 30 Years through 2100 Using NASA's MERRA and CMIP5 Simulations. In *2015 International Conference for Energy and Climate for the Energy Industry (ICEM 2015)*, number NF1676L-21913.

Weiskopf, S., Cushing, J., Morelli, T. L., and Myers, B. (2021). Climate change risks and adaptation options for Madagascar. *Ecology and Society*, 26(4).