Framing the state-of-the-art on the use of software and digital tools for subsurface hydrology and hydrochemistry in the African continent

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ABSTRACT

Groundwater is a resource of increasing prominence in Africa whose potential has still to be developed in full capacity. Digital tools may support and boost efficient data management so that more technically sound and even community-based decisions may be made. In this view, development and diffusion of robust open source and free software constitutes a cornerstone to enhance groundwater management, thus empowering as much as possible research and technical units in academia, water authorities, and private companies, with a special regard to communities/countries with limited resources. In this context, we attempt to frame the state-of-the-art on the use of digital tools for sustainable groundwater management in the African continent. Starting from a comprehensive literature review and performing investigations via a structured questionnaire on ongoing practices at institutional and private sector level, the results of the research allow a clear view on the present level of knowledge and on the diffusion of such tools.

The most widespread digital tools for groundwater resource management are calculation spreadsheets, then Geographic Information Systems applications, followed by numerical modelling tools, and last advanced tools for statistical analyses. We used experiences in groundwater numerical modelling, retrieved in scientific papers with African scientists as first author, as a proxy for assessing the level of digitalisation in groundwater resource management in Africa. The data gathered show that at present the use of digital tools/groundwater numerical models is deemed to be an occasional activity, mostly applied for large engineering projects or basic modelling studies, and rarely used for planning and management of the resource. All in all their use in the period 2000-2020 can be considered low. Groundwater numerical modelling and/or other digital tools are still seen as research oriented tools. There is a clear difference in their use between North Africa, where five countries barely produced in 20 years the same number of studies than Sub-Saharan African countries.

When evaluating current will in African institutions (academic and governmental) digital tools are recognised as needed tools for groundwater resource management at national or regional level. Skills and capacities for dealing with groundwater management using digital tools are considered missing by the 50% of our sample. As such, the need for capacity building on the use of digital tools for groundwater management is (extremely) high.

Commercial software solutions still dominate the market in Africa (i.e. in GIS applications and Graphical User Interfaces for numerical modelling), while open source ones appeared in increasing trend of usage in the last years. A large part of the interviewed prefer open source software (71%), to commercial ones (22%). Open source software is preferred because of the possibility of developing tailored applications thanks to the code availability, software reliability and easy to use. Open source and free software would be used if adequate training would be provided by 70% of the respondents, but a further 30% would require also support in the software use.

Finally, main barriers in the use of digital tools are: i) scarcity of data to develop a model, ii) inadequate resources to develop and maintain a model, and iii) missing capacities. Digitalisation of groundwater-related data in digital archives is a need. On another view, the main problems are related to the lack of computing skills and lack of computing resources. In addition to these, the lack of adequate and well-functioning data transmission networks (Internet) is considered the main bottleneck in favouring the spread of new technologies.

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FOREWORD

The present report details the activities run in the framework of the contract *Framing the state-of-the-art on the use of software and digital tools for subsurface hydrology and hydrochemistry in the African continent*.

Groundwater is a resource of increasing prominence in Africa whose potential has still to be developed in full capacity as the natural storage is high, the water quality is often good, and the infrastructures are more affordable to poor communities (Adelana and MacDonald, 2008). However, data on groundwater systems are sparse and the current state of knowledge is low, hence constituting a serious limitation to the sustainable development of the groundwater resources (Xu et al., 2019). Still, despite the relevance of groundwater, the available technical and scientific body of knowledge in Africa is generally limited and focused on the local scale, as related to both the complexity of the aquifer systems and the lack of reliable and comprehensive datasets. The current detailed activities addressed the need for having an updated state-of-the-art overview on the use of software and digital tools for subsurface hydrology and hydrochemistry in the African continent.

Purpose, objectives and scope

The general objective of this research is that of framing the state-of-the-art on the use of software and digital tools for subsurface hydrology and hydrochemistry in the African continent. Starting from a comprehensive literature review and performing investigations on ongoing practices at institutional and private sector level, the results of the research allow a clear view on the present level of knowledge and on the diffusion of such tools. A particular focus, is dedicated to review the use of Open Source tools in groundwater-related data management, analysis and modelling in Africa, thus detailing the current status and future perspective, aiming at providing suggestions on potential robust and reliable available tools to be exploited.

The multifaceted objective of this research is that of deriving, out of the research carried out, ideas and actions for pushing digital groundwater management in Africa, with reference to the specific African context, and in particular to devise needed and effective capacity building actions in order to achieve the defined goals. The research results finally allow an insight on the needs and priorities for digital tools to improve groundwater resource management, thus highlighting directions for supporting capacity building efforts.

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1. Introduction

Groundwater is a resource of increasing prominence in Africa whose potential has still to be developed in full capacity as the natural storage is high, the water quality is often good, and infrastructure is more affordable to poor communities (Adelana and MacDonald, 2008). However, data on groundwater systems are sparse and the current state of knowledge is low, hence constituting a serious limitation to the sustainable development of groundwater resources, especially for what concern Sub-Saharan Africa (Xu et al., 2019).

Why dealing with digital tools for groundwater resource management

While it is clear that data gathering in order to achieve a certain level of knowledge is of outmost importance for many African aquifer systems, there is at the same time the need of technologies that may help in managing this data effectively. Information and Communication Technology (ICT) may provide several tools to this aim.

Standardized and digitally referenced groundwater data is required to enable the detailed analysis of local, regional, and country-wide and transboundary groundwater needs and trends, to prioritize issues, areas and techniques to focus limited resources on, to enable the prediction of future scenarios of groundwater conditions, and to investigate the linkages of groundwater to other environmental issues.

We refer as digital tools to all those Information and Communication Technology tools that may support groundwater data gathering, archiving and analyses, spanning from digital ground and remote sensors, to Geographical Information Systems (GIS), to groundwater numerical modelling up to advanced artificial intelligence methods for data-based groundwater resource planning and management.

The use of digital tools is relevant as such tools may provide a dynamic and easily updatable view on the resource available, used, and potentially exploitable without the need of relying on analogical or paper-based static analyses. In that, these tools allow the possibility to maintain digital archives and to perform predictive simulations – even for exploring impacts of/or adaptation to climate change. Their diffusion is nowadays facilitated by two main factors: availability of computing resources at low cost and of open source and free software.

Why we used groundwater numerical modelling as a proxy of digitisation in the groundwater sector

Geographic Information Systems and spatial databases are a consolidated and cross-cutting technology, spread at global scale in the last twenty years, with applications, spanning through such different fields as urban and environmental, as well as water management. On the other hand, the widespread adoption of groundwater flow numerical modelling outside the academia is more recent and may provide better evidence of the recent trends in the level of digitalisation in the water sector, particularly in low income countries. Building groundwater flow numerical models has become easier at many organizations, whether in the private or public sector, i.e.. governmental and academic/research Institutions. Open source codes and even user-friendly modelling environments have become increasingly available, provided that the shortage in proper skills and availability of advanced computational resources still act as a major bottleneck against effective implementation at global scale.

More advanced applications based on Artificial Intelligence (AI) are still in their infancy in the water sector, both in academia and in applied research and, consequently, in daily water management, even in high income countries. Definitely, they cannot be considered as a reliable proxy.

Based on the reasoning above, our research focused on the trends over the period 2000-2020 in the use of groundwater flow numerical models and the further adoption of coupled solute transport and density-dependent flow models.

Why modelling is an important tool

Among the available digital technologies, physically-based and distributed groundwater numerical models (coupling ground- and surface-water and unsaturated zone processes, and incorporating climate, land use, hydrological and hydrochemical data) may represent comprehensive and dynamic tools to target water resource management issues (Rossetto et al., 2018; Refsgaard et al., 2010). These tools allow simulating the distribution of the water resource in space and time, taking into account anthropogenic stresses and providing sound-scientific information relevant to decision makers (Pullar and Springer, 2000). They may support the development of highly informative representations of hydrological systems by: i) combining all the available spatial and non-spatial data in a single framework; ii) allowing update and improvement as new data are gathered; iii) providing information in space and time to water managers; iv) offering relevant predictive functions, thus allowing evaluation on how a hydrological system might behave under different scenarios of natural and anthropogenic constraints. Anderson et al. (2015) discuss in detail the potential applications of such tools, while Singh (2014) presents a review on the use of numerical groundwater models for managing the groundwater resource. Examples of applications to fulfil water regulation requirements may be found in Vázquez-Suñé et al. (2006), Shepley et al. (2012), and Moran (2016).

Numerical groundwater flow models are playing an increasingly important role in recent years. They may substantially help in supporting science-based decision making, by allowing at a first step water budget calculations, identification of most relevant inflow/outflow terms, as well as their spatial and time variations. Once basic understanding is achieved and after calibration, models may be used for predictive simulations, leading to information relevant to sustainable groundwater resources management policies (i.e. irrigation in agriculture, water use in industry and for human supply), prediction of climate change impacts, support feasibility and assessment of large infrastructural projects (i.e. waterways, tunnelling, damming, contaminated aquifers remediation). Yet Moore (1979) stated as groundwater models could be used in planning the development of groundwater and the conjunctive use of ground- and surface water with a high degree of confidence, and may provide the water planner with tools to evaluate problems such as groundwater availability, accessibility, quality, cost of development, or effect of exploitation on surface water bodies.

A number of codes and related software, either open source, free or proprietary is available to support the development of groundwater models and integrated hydrological models, as, among others, MODFLOW (and its entire USGS family), FEFLOW and Hydrogeosphere. Starting from the U.S. Geological Survey MODFLOW suite, MODFLOW (McDonald and Harbaugh, 1988) is a modular finite difference numerical groundwater flow model, which solves the groundwater flow equation. The program is widely used by hydrologists and hydrogeologists worldwide to simulate the flow of groundwater through aquifers. The source code is free public domain software, written primarily in Fortran, and can compile and run on Microsoft Windows or Unix-like operating systems. FEFLOW (Finite Element subsurface FLOW system; Diersch, 2014) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media and fractured media. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. HydroGeoSphere (HGS, Brunner and Simmons, 2012) is a 3D control-volume finite element groundwater model, and is based on a rigorous conceptualization of the hydrologic system consisting of surface and subsurface flow regimes. For each time step, the model solves surface and subsurface flow, solute and energy transport equations simultaneously, and provides a complete water and solute balance.

Several Graphical User Interfaces (GUIs) are available in the market to help numerical model building in the pre-process, processing or post-processing phase (Visual MODFLOW, Guiguer and Franz, 1996; Groundwater VISTAS, Rumbaugh and Rumbaugh, 2011; GMS, Aquaveo, 2007; ModelMuse, Winston, 2009). Also, close/tight coupling solutions for integrating the numerical codes into the GIS are available (e.g., FEFLOW, Crestaz et al., 2012; MODFLOW, Shapiro et al., 1997; MODFLOW Analyst, Aquaveo, 2012; SID&GRID, Rossetto et al., 2013; FREEWAT, Rossetto et al. 2018). The most used GIS software for developing close/tight coupling is ESRI GIS software (ESRI, 2011), followed by ARGUS One (Argus Holdings Ltd., 1995), QGIS (QGIS Development Team, 2009), and MapWindow GIS (Ames et al., 2008). GRASS-GIS (GRASS Development Team, 2017) and gvSIG (Anguix and Díaz, 2008; gvSIG Association, 2010) were used in one coupling experience each. Most of the solutions are developed using free and open source GIS software (e.g., Bhatt et al., 2008, 2014; Carrera-Hernandez and Gaskin, 2006). Several modelling codes are open source and freely available (e.g., MODFLOW). It must be noted that the openness of a code is increasingly a relevant factor in scientific analysis, as it constitutes a guarantee for reproducibility and reliability of the analysis performed (Ince et al., 2012; Hanson et al., 2011) and fast deployment of the code (Dile et al., 2016). Codes neither open nor free, among them the well-known MIKE SHE (Hughes and Liu, 2008) and FEFLOW (Diersch, 2009), restrict the usage only to those able to buy such software (i.e., high income countries; Dile et al., 2016). The cost of the software may then constitute a barrier to the use of advanced ICT tools for groundwater management. As for modelling codes, commercial GISs, besides the licensing costs, often bring concerns about proprietary data structures, rigidity in data-models, and platform dependence (Bhatt et al., 2008, 2014).

2. Objectives and description of work

The multifaceted objective of this research is that of deriving, out of the research carried out, ideas and actions for pushing digital groundwater management in Africa, with reference to the specific African context, and in particular to devise needed and effective capacity building actions in order to achieve the defined goals.

With this research we attempted to frame the state-of-the-art on the use of software and digital tools for subsurface hydrology and hydrochemistry in the African continent. We aimed at assessing the level of digitalisation for sustainable groundwater management in Africa using two independent approaches:

1) a dedicated literature review on scientific and technical documents reporting the use of digital tools via the worldwide web and our network;

2) by mining the replies to 220 dedicated questionnaire compiled by African experts in groundwater resource management and constituted by 83 questions divided in four sections.

During the analyses, we cross-validated the results of the literature review with those gathered through the questionnaire.

In this report, Section 3 presents the activities run to perform the literature review and the results gathered, while Section 4 presents the activities run to perform the survey and the related results gathered. Section 5 discusses the results and gather conclusions out of the analyses performed. The report is complemented by three Appendixes (A, B and C; reference is made in the text).

Working approach and methodology

The work foreseen was organised in three phases as follow:

Phase 1 – Literature review

A detailed literature review was undertaken searching last 20-years peer-reviewed scientific papers, academic documents (MSc and PhD thesis), conference proceedings, books, and published technical reports. This allowed a comprehensive picture of the studies/activities performed using modelling tools for groundwater resource management in Africa. In this phase, the following tasks were run:

Task 1.1 Assessment on available data on groundwater hydrology. This task consisted in a survey of available free datasets on groundwater in the African continent. The assessment was performed both by searching the worldwide web and requiring information to large international organisation countries, having potentially funded such initiatives in the past, and relevant national institutions in Africa. The list is available in the file *web_data.xls* in the folder *annex_1*.

Task 1.2 Search and review of peer-review technical/scientific papers. This task consisted on reviewing the last 20 years (from the year 2000) and year 2020 peer-reviewed papers in the scientific literature dealing with groundwater data management, analysis and numerical modelling in African countries. Scientific databases were searched using relevant technical keywords linked to the geographical ones. The review on these modelling efforts is presented in this final report along with a synthetic list (file *modelling_documents.xls* in folder *annex_2*) with main information on each document. All the documents are available in a dedicated folder in the B2DROP web archive (folder annex_3).

Task 1.3 Review of published/unpublished reports. This review includes published and unpublished reports that are available through the worldwide web. The world wide web and African and International institutions and companies were contacted in order to get information on published documents, and potentially retrieve these documents/reports, on the subject of the research. To this aim, besides the web, Scuola Superiore Sant'Anna exploited its current network and the network created within the ACE WATER 2, including governmental authorities, water ministry, environmental protection agencies, universities, research centres and private companies. The review on these modelling efforts is presented in this final report along with a synthetic list (file *modelling_documents.xls* in folder *annex_2*) with main information on each document. All the documents are available in a dedicated folder in the B2drop web archive (folder annex_3).

Task 1.4 Creation of a spatial database. A spatial database was created. It contains a polygon shapefile showing the approximate boundaries of the models built in the African continent retrieved by the papers and technical documents reviewed. This allows presentation of this information with its geographical references in order to provide a map of the spatial distribution of the retrieved studies. The areal extent of the modelled domains is provided in geographical format as geopackage file in the folder *annex_4.*

Phase 2 – Investigation on the use of specific open source software tools for groundwater resource management

The objective of this phase was to gather an insight on the software currently used in public and private African institutions for groundwater management focusing on needs and priorities evidenced by these institutions. A specific section was dedicated to the use of free and open source software and to highlight capacity building needs. The survey allows to assess the current status and to highlight future perspectives in African continental, regional and country Institutions, operating in the field of groundwater management.

In this phase, the following tasks were run:

Tasks 2.1 On-line questionnaire design and preparation. A structured questionnaire was designed including four different sections (for a total of 83 questions posed) to get information on the present use and the level of usage of software tools for groundwater resource management. The first section served to characterise the respondents, section 2 to get information on current status of groundwater resource management and the use of digital tools in the institution and the Country of the answerer. The third section helped to

gather information on current status of groundwater resource monitoring. Finally, in the fourth section we asked about perspective on modelling and digital tools for groundwater resource management. This in order to retrieve information and opinions for boosting the use of digital tools for groundwater resource management in Africa.
A specific section was dedicated to the diffusion and the willingness to adopt open source and free solutions in respect to commercial ones. Present and ongoing EU regulations on data protection were followed after consultation with Scuola Superiore Sant'Anna Data Protection Officer. The final version of the questionnaire is delivered in the folder annex_5 (in English and French).

Tasks 2.2 On-line questionnaire distribution. The questionnaire was distributed in anonymous form. Aside from exploiting Scuola Superiore Sant'Anna current network and the network created within the ACE WATER2 project, in order to achieve a statistically significant dataset, a search (using mostly scientific databases) dedicated to retrieve relevant contacts dealing with groundwater and, when possible, groundwater modelling/data management was run. Only African experts were selected to participate in the survey.
We retrieved more than 800 contacts, with related mail addresses. The number of addresses retrieved is 8 times larger than the one foreseen in the ToR (in the number of 100 institutions/entities). The questionnaire was then distributed online to the retrieved contacts. Personnel was contacted via e mail, a minimum of three times (up to a max of five), presenting the questionnaire and its scope, and asked to complete it. We validated 757 e mail addresses, and 229 individuals fully replied to the questionnaire (30.3% of the whole sample). We gathered at least 3 answers from 24 African countries.

Task 2.3 Retrieved information analysis and reporting. The gathered information were analysed to the get a clear view on:
o the diffusion and usage of software for groundwater resource management in Africa;
o the needs and priorities related to such software;
o the diffusion and willingness to adopt open source and free software tools;
o capacity building needs.

Phase 3 – Report finalisation and scientific paper preparation

A technical report, summarizing the methodology and achievements of the work done, being the basis to support future training and capacity building activities, is presented along with Annexes.

Out of the research outcomes, a scientific paper is under preparation, the tentative title being "Review and state-of-the-art on the use of digital tools and groundwater numerical modelling for groundwater resource management in Africa". The paper submission was delayed due to a more ambitious plan as related to the much larger audience of interviewed stakeholders. At present six African experts were also involved in drafting the document in order to achieve a view also shared with researchers living the African context. They are: Yongxin Xu (South Africa), Faye Serigne (Senegal), Chirckbene Anis (Tunisia), Olago Dan (Kenya), Kebede Seifu (Ethiopia), Yidana Mark (Ghana). More African experts will be involved in order to finalize a paper that is expected to comprehensively provide a view of the most represented countries in this research. The paper will be submitted within the end of January 2021 to a relevant Q1 Scopus index scientific journal.

A PowerPoint presentation of about 20 slides summarizing the research outcomes is also delivered.

3. Literature review

A desktop analyses on groundwater flow modelling experiences in the African continent over the last 20 years (2000-2019) and in 2020 was carried out. We searched both technical/scientific peer-reviewed papers and not peer-reviewed technical reports or academic documents (i.e. technical documents, conference proceedings, PhD thesis, MSc thesis). The peer-reviewed papers search was carried out using the search engines stated in Table 3.1. Different searches were performed varying the keywords (Table 3.2), in order to make the search more specific and incisive. Additional documents were found adding the name of all the African Countries instead of *Africa* to the keywords. Further documents were retrieved by contacting individuals in our research network and by controlling the reference section of each retrieved paper.

Search engine	**Web address**
Science Direct	sciencedirect.com
Springer	link.springer.com
Taylor & Francis	tandfonline.com
Scopus	scopus.com
Web of Science	webofknowledge.com
IWA publications	iwaponline.com
Africa Groundwater Literature Archive	bgs.ac.uk/africagroundwateratlas/archive.cfm
Google search engine (for grey literature)	Google.com

Table 3.1. Search engine used.

Keyword used
"groundwater model" AND Africa
"groundwater flow model" AND Africa
"groundwater numerical model" AND Africa
"groundwater flow numerical model" AND Africa
"hydrogeological model" AND Africa
"solute transport model" AND Africa
"contaminant transport model" AND Africa
modflow AND Africa
feflow AND Africa

Table 3.2 Keyword used for the search.

A specific search for documents on the Countries within the watershed of the Senegal River basin (Senegal, Mali, Mauritania and Guinea) was carried out using the Google search engines. Since the search performed in English gave few results, the documents were searched in French, using the keywords *"Modelisation de la nappe/ Modelisation du nappe"* and the name of the Country. We included in the results also MSc/PhD thesis discussed in non-African universities (i.e. in Europe). The identified documents were saved and organized in an Excel sheet. All the retrieved documents found were geolocated on a map on a GIS project. The information presented in Table 3.3 are reported, when available for each document.

Field name	**Metadata**
ID	Unique and progressive document identifier
Publication year	Document publication year
Document type	Research paper, conference proceeding, MSc thesis, PhD thesis, technical report
Peer-reviewed	Yes/Information not available
Document title	Document title
Language	Language of the document
Author(s)	Name of the document's authors
Journal/book/conference	Journal or book or other in which the document is published (if any)
Reference	Full bibliographic reference
Indexing in SCOPUS	Yes/No
SCIMAGO rank	SCIMAGO quartile of the journal in the year when the scientific paper was published
Objective of the study	Main objective of the work described in the document
Objective short	Synthetic objective of the modelling study
Specific objective	Specific objectives of the work described in the document (if any)
Theoretical/Applied	Main aim of the study regarding to new knowledge acquisition (theoretical) or application
Main outcome	Main results of the study
Country	Country where the study was performed
Model name	Name of the model (if any)
Spatial relevance of the model	Spatial relevance of the implemented model (local, sub-regional or regional)
Main aquifer investigated	Main aquifer investigated in the study
Transboundary aquifer	Transboundary aquifer in which the study is located (if any)
Watershed	Watershed in which the study is located (if any)
Code(s) used for the simulations	numerical code used for the model implementation and simulations
GUI	Graphical User Interface used in the study (if any)
Approximate domain extension	Approximate extension of the model domain (in Km^2)
Simulation condition	Temporal conditions in which the simulations have been run (steady and/or transient state)
Calibration method	Calibration methodology used (if any)
Number of model layers	Number of model layers used
First author institution country	Country of the Institution of the first author
Number of authors:	Number of authors of the document
Number of authors from non-African institutions	Number of authors not associated to an African institution
Funding source	Source of the funding provided to perform the study (if available)
Data availability	Availability on open access mode of the data used to build the model
Data availability (where)	Web address for data availability
Abstract	Abstract of the document
Document availability	Document availability
DOI	Digital Object Identifier

Table 3.3. Information retrieved from the surveyed documents.

We contacted via e mail the authors of the retrieved documents about the data used, and about their willingness to share the data used during the development of their work. As basic request, we asked the availability of the model domain shapefile. In case they agreed to provide more information, the following step was to send them a specific chart to be filled up with detailed information regarding the specific numerical model. All the authors of the identified documents were contacted. Only 38 contacted authors answered; 8 authors sent the model boundary shape file and 2 authors sent the sources of the input data used to develop the model.

We based our analyses only on the scientific papers, using numerical modelling as a proxy of the level of digitalisation. The following information were analysed:

- number of papers in the last 20 years (2000-2019), the number of papers divided per North Africa /Sub-Saharan Africa;
- spatial distribution of these papers;
- number of scientific paper with a scientist from an African institution as first author versus those with first author not from an African institution;
- type of numerical codes in papers with first authors from an African institution as first author versus those with first author not from an African institution;
- use of graphical user interface in papers with first authors from an African institution as first author versus those with first author not from an African institution.

In the following sub-section, we briefly present the main results of the literature search first for all the retrieved documents, then only for the peer-reviewed scientific papers.

3.1 Results of the literature review

A total of 394 documents produced within the period 2000-2020 (to date) were found as result of the whole literature review. Table 3.4 sums up the type of documents retrieved and the number for each type of document; only 8% of the retrieved documents are in French, all of the others are in English. All the search results, divided per Country, can be found in Appendix A at the end of this document. Table 3.5 presents the results of the search related to the four countries included in the Senegal River basin.

Type of document	Total number	Language	
		English	French
Research paper	280	272	8
Conference proceedings	34	32	2
MSc Thesis	16	11	5
PhD Thesis	21	11	10
Book chapter	13	13	-
Book	2	2	-
Technical report	27	22	5
Research paper in book	1	1	0
Total	394	364	30

Table 3.4. Type and number of retrieved documents.

	Search results in English	Search results in French	Total
Senegal	3	15	18
Mali	5	2	7
Mali/Mauritania	-	1	1
Mauritania	-	-	-
Guinea	-	-	-

Table 3.5. Retrieved documents on the River Senegal basin.

Distribution in space and time of the retrieved reports

All the documents retrieved are geolocated in point format in Figure 3.1; in this picture the current representation of the main African transboundary aquifers is also reported. In Figure 3.2 we present the boundaries of the modelled domains as digitised and georeferenced using the maps retrieved in the papers. As a special focus is given on West Africa and the Senegal river basin, a synthetic description of the retrieved documents for that area (in particular for the Senegalo-Mauritanian Basin, the Taoudenì Aquifer System, and the Iullemeden Aquifer System) is given in Appendix C to this report.

Referring to the period 2000-2019, the majority of the identified documents were published in the last decade (69% of all the documents). In particular, 43% out of all the documents were produced in the last five years, as shown in Figure 3.3. For the year 2020, the documents retrieved account for 10% out of the documents retrieved in the 20 preceding years. Figure 3.4 compares the percentage of retrieved documents in time for North Africa (NA, Egypt, Libya, Algeria, Tunisia and Morocco) to those for Sub-Saharan African countries (SSA), defined as the countries that are fully, or partially, located South of the Sahara (Xu et al. 2019). It is worth noticing that the five NA countries contribute to 43% of the produced documents in the period 2019-2020. This rate increased to 47% in the last lustrum and it is even bigger in 2020 (59%).

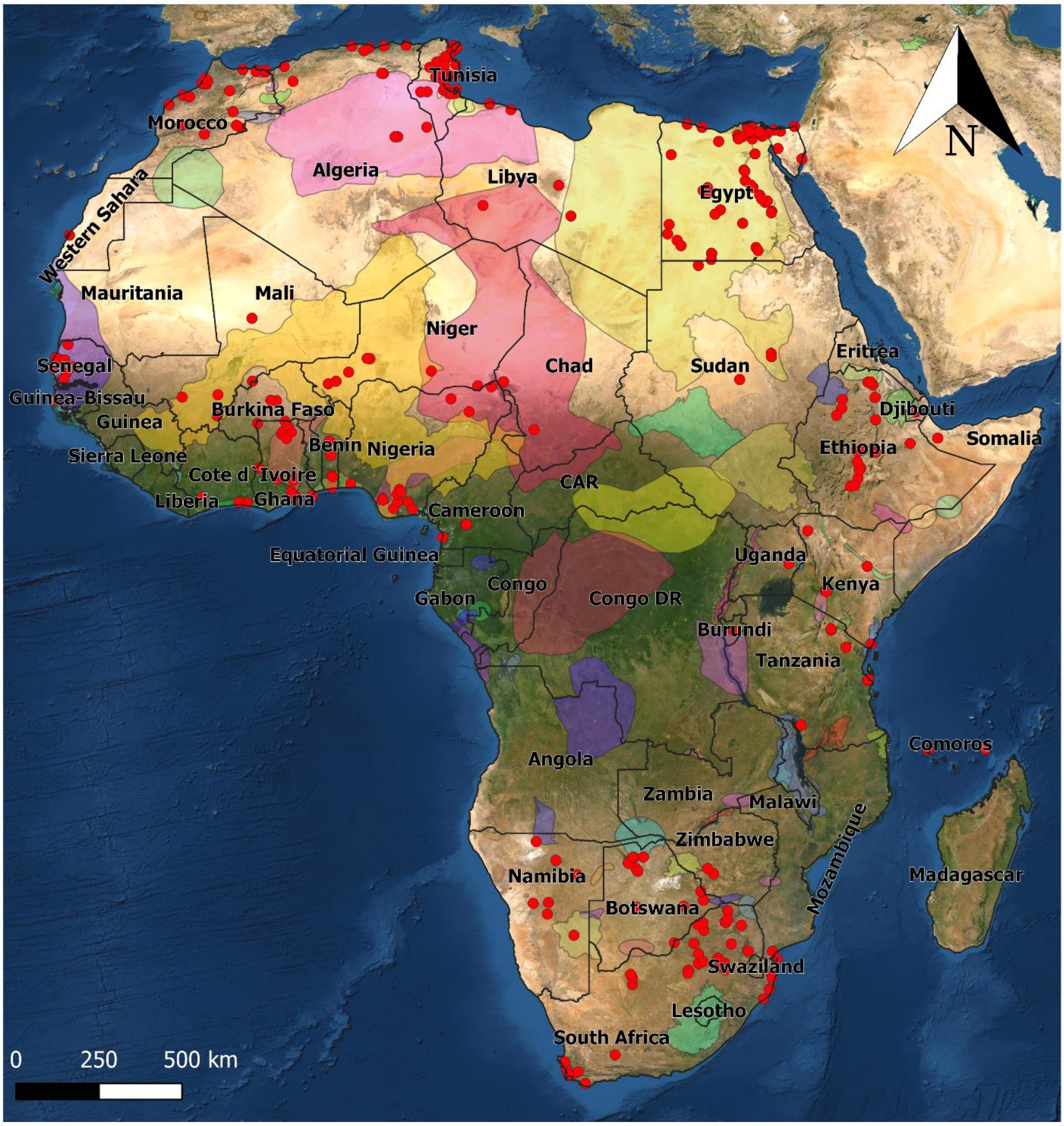

Figure 3.1. Spatial distribution of all the documents found. In the image the African transboundary aquifers are also represented (source IHP-UNESCO, 2015 modified).

Figure 3.5 presents the number of documents retrieved per each Country. Most of the identified documents are related to modelling exercises run in Egypt (79), then South Africa (49) and Tunisia (40). For Niger, Ethiopia, Ghana, Morocco and Nigeria, we retrieved a number of documents ranging between 20 and 30. We did not retrieve any published document for the Countries not mentioned in the chart.

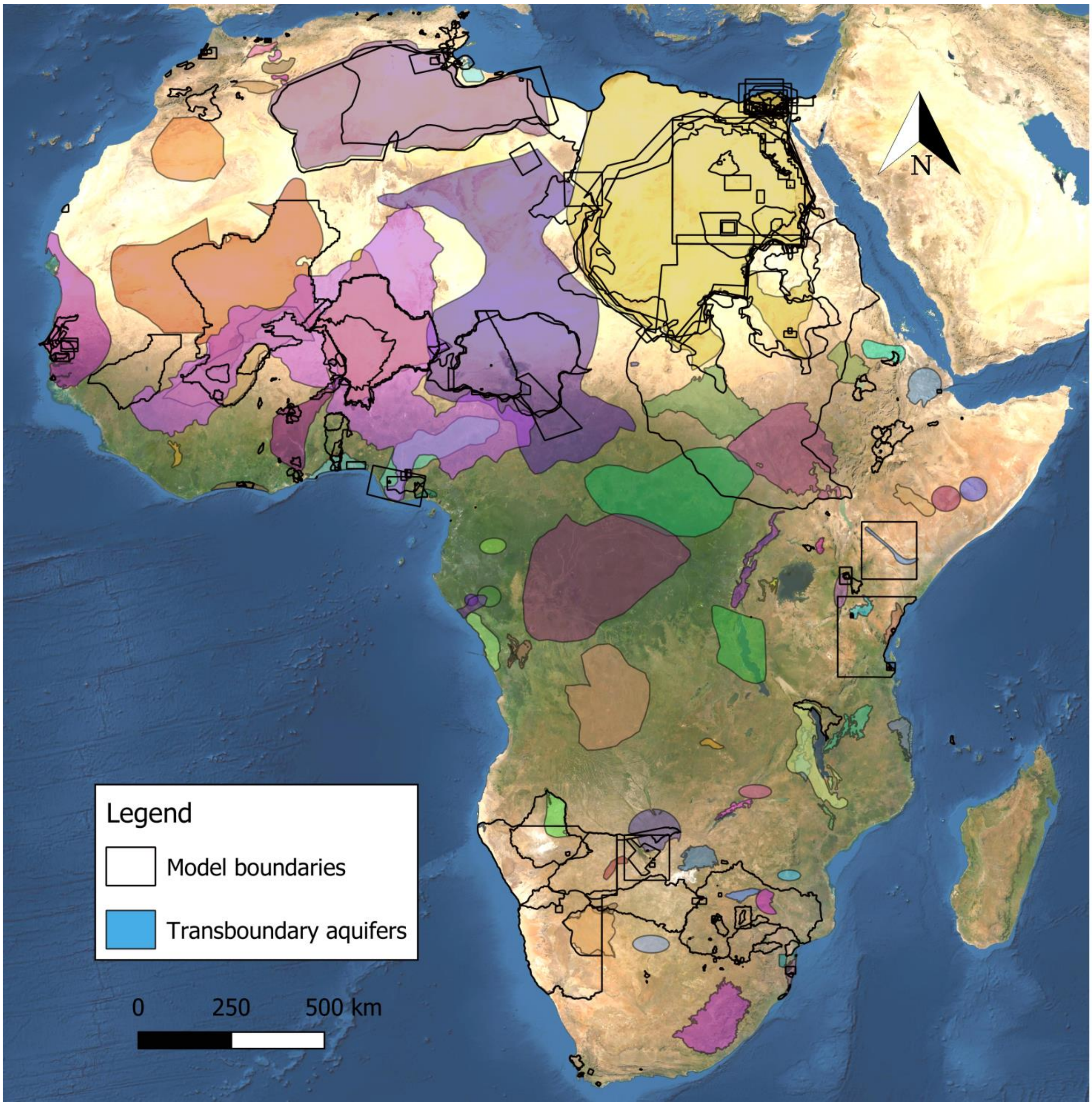

Figure 3.2. Boundaries of the modelled domains retrieved during the literature review. In the image the African transboundary aquifers are also represented (source IHP-UNESCO, 2015 modified).

The analyses on scientific papers

As not all of the technical reports, conference proceedings or thesis may have been easily available via the web or throughout our contacted channels, we refer in the following analysis only to scientific papers, for which we assume to have performed an exhaustive search using the above-mentioned scientific databases. Moreover, some of the scientific papers are published as an outcome of some of these general documents. Then, considering only scientific papers avoids the risk of analysing two times the same study.

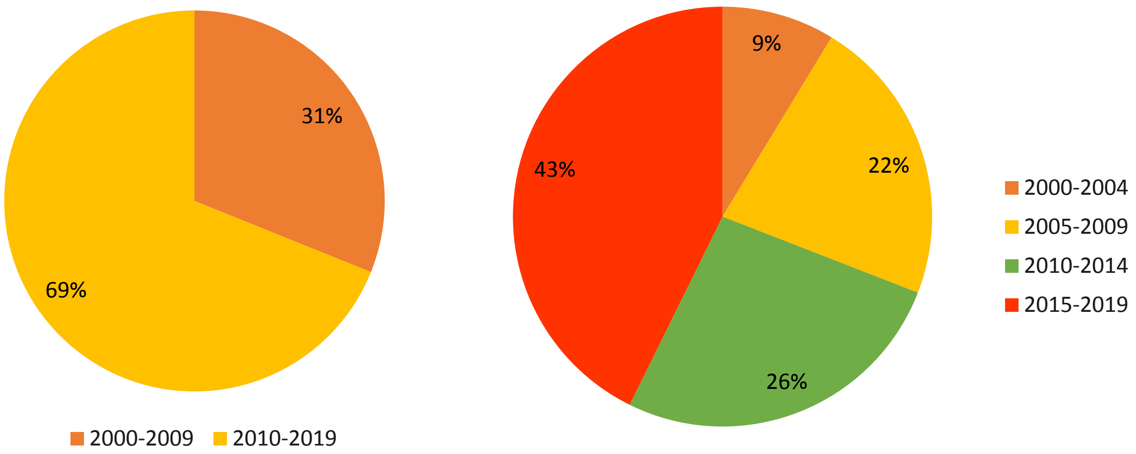

Figure 3.3. Percentage of all the documents found divided by decades and lustrum intervals (the data are shown in Tab. A1 in Appendix A).

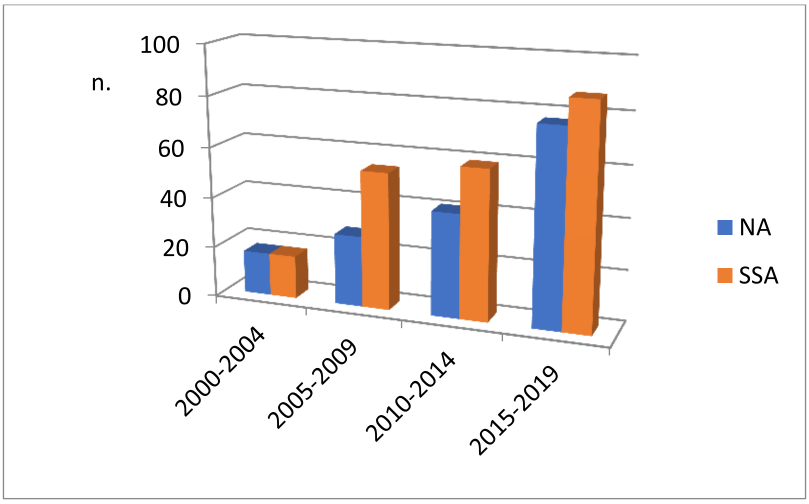

Figure 3.4. The percentage of documents found for NA and SSA Countries divided by years intervals (the data are shown in Tab. A2 in Appendix A).

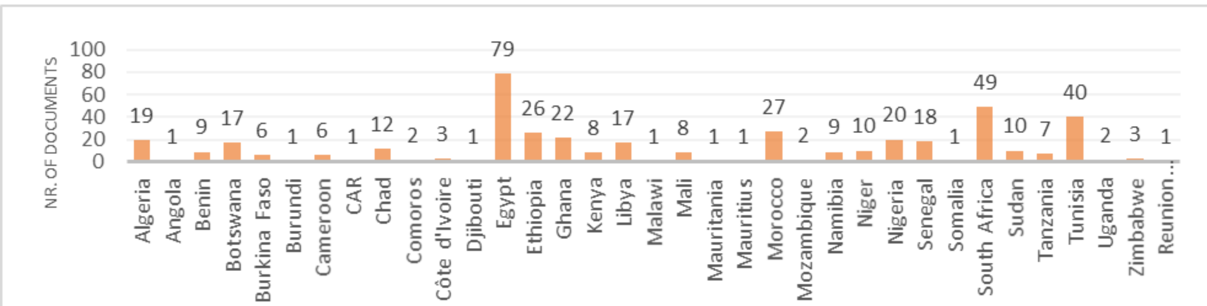

Figure 3.5 Documents found divided per Country.

In our search, we retrieved a total of 280 scientific peer-reviewed papers (272 in English and only 8 in French). Out of this number, 139 are related to studies performed in NA countries and 141 in SSA countries. Still 50% of these papers regards studies run in only 5 African countries. Figure 3.6 presents the number of papers retrieved per each Country.

The largest number of published documents is related to studies performed in Egypt (65), Tunisia (35) and then South Africa (23), Morocco (23) and Ghana (21). In SSA, most of the studies deal with areas in South Africa, Niger, Nigeria, Ethiopia, Ghana. Based on the total number of the published research papers the use of such tools in Africa increased about 5 times in the last five years respect to the period 2000-2004. Given the data for 2020, the last five years (2015-2019) rate is maintained and even improved.

Figure 3.7 shows the percentage of total documents per lustrum. The number of published studies passed from 18 (7%) in 2000-2004 to 100 in 2015-2019 (41%). In 2020 only, we retrieved 36 studies. This shows that the trend in using groundwater numerical models is still increasing. Figure 3.8 shows the percentage of total documents divided per studies run in NA and SSA still per lustrum.

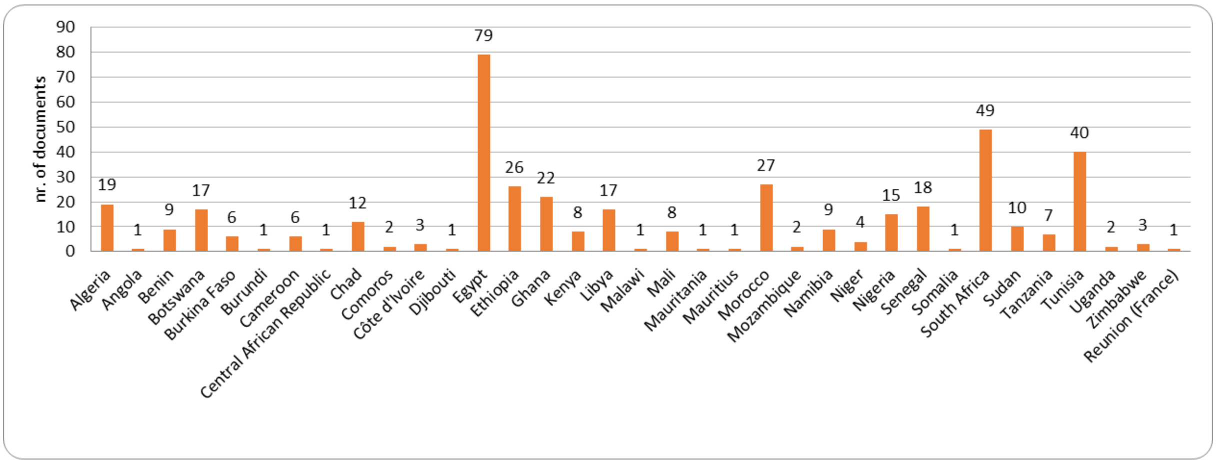

Figure 3.6. Scientific papers divided per Country.

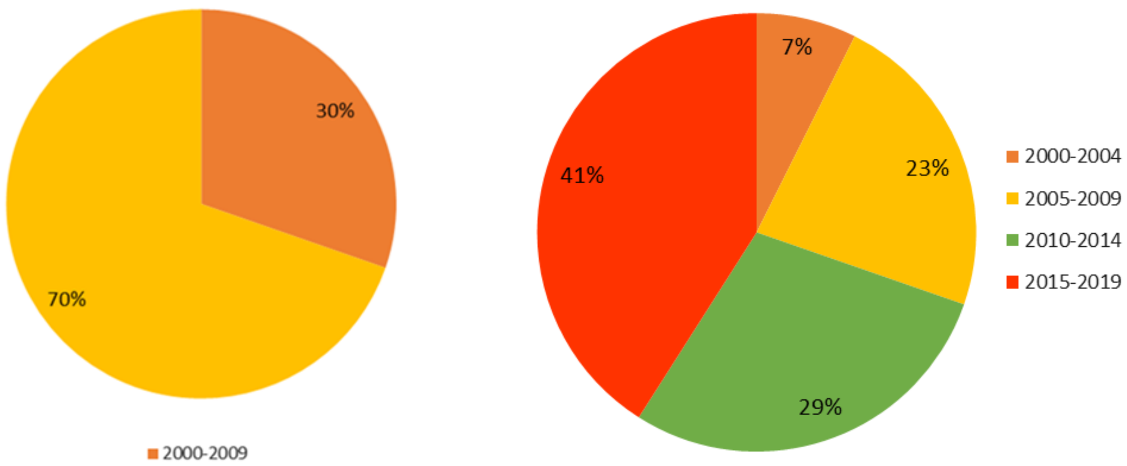

Figure 3.7. Percentage of all the scientific papers found divided by decades and lustrum intervals(the data are shown in Tab. A3 in Appendix A).

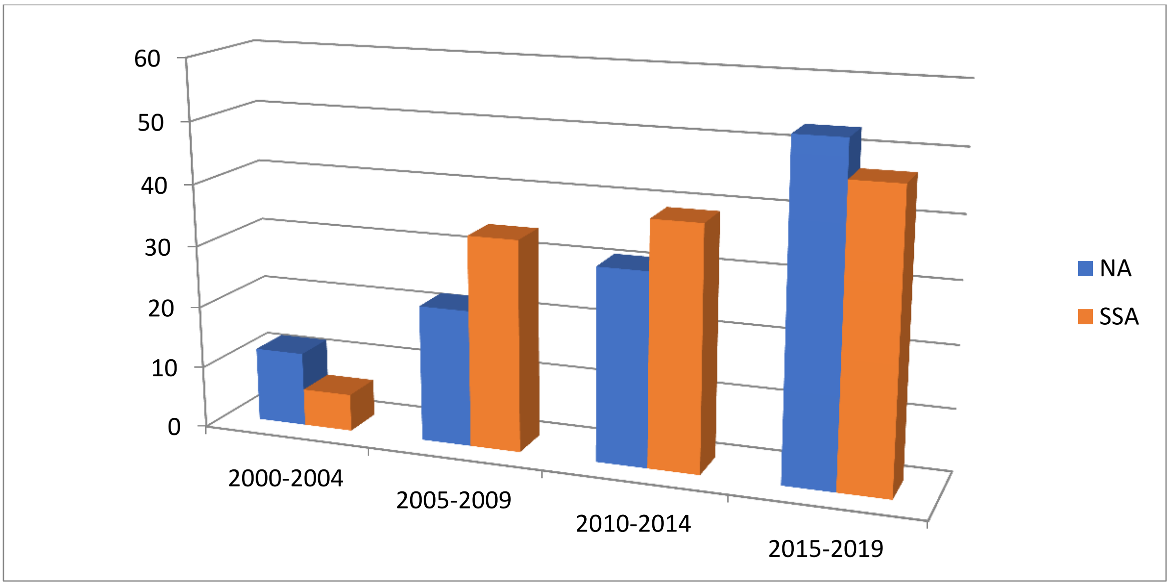

Figure 3.8. The percentage of scientific papers for NA and SSA Countries divided by years intervals Figure (the data are shown in Tab. A4 in Appendix A).

Most of the studies were developed using the MODFLOW code (225), followed by MT3D/MT3DMS, SEAWAT (19), and FeFlow (15) (Figure 3.9). The number in the category "Unknown" (11) depends on the fact that in some cases the text of the papers was not accessible and/or the code used for the simulations was not stated in the document text (6). Both studies in NA and SSA have been massively using the MODFLOW code.

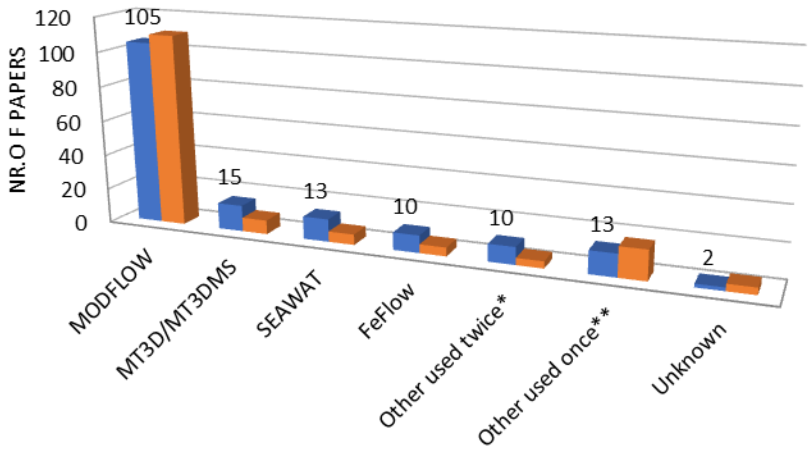

Figure 3.9. Number of scientific documents per code used in NA and SSA (the data are shown in Tab. 5A in Appendix A). *GroundWater, MICROFEM, MODPATH, TOUGH2, WEAP, MIKE-SHE. **CODESA-3D, FEMWATER, HYDRUS-1D, Hysuf-FEM, iMOD, MODCOU, FEN, CORE2DV4, MOGA, Wetspass, NETHPATH, GARDENIA, GEMFLOW, HydroGeoSphere, MARTHE, HYDROS, PMPATH, OpenGeoSys, PHAST 1.2, ps2D, d3f, SPRING, SUTRA, WINFLOW, WINTRAN, YAGmod.

The analyses on scientific papers with first author an African scientist

As a considerable number of studies (38%) has been led in 2000-2019 by scientists non-affiliated to African Institutions, we analysed the scientific papers where scientists affiliated to an African Institution are listed as first authors. In this case, we assume that the first author has been either performed the bulk of the research or has been leading the research. Figure 3.10 shows the number of scientific paper with a scientist from an African institution as first author versus those with first author not from an African institution, and those without African co-authors. To this regard, the African lead papers increased about six times, passing from 11, for the period 2000-2004, to 69 in the period 2015-2019 (Figure 3.10). At the same time, the number of papers published on studies performed in Africa with first author not-African or with no-African authors remained stable since 2005. When looking into the geographical differentiation (Figure 3.11), it is clear that the afore-mentioned increase is due to an increase in studies published in North Africa. Figure 3.12 presents the country distribution of such papers.

We then analysed the codes for numerical modelling used in the papers with an African first author in NA (Figure 3.13) and in SSA (Figure 3.14). The most used code is MODFLOW, which is a free and open source code. The only noticeable difference is related to the use in NA of codes to be coupled to MODFLOW, that is MT3D and MT3DMS and SEAWAT (also free and open source codes), for the simulation of solute transport in aquifers and density-dependant problem. As these codes requires additional knowledge on groundwater hydrology and hydrochemistry, or contaminant hydrogeology, we may infer that potentially in NA these disciplines are more pronounced that, in general, in SSA countries.

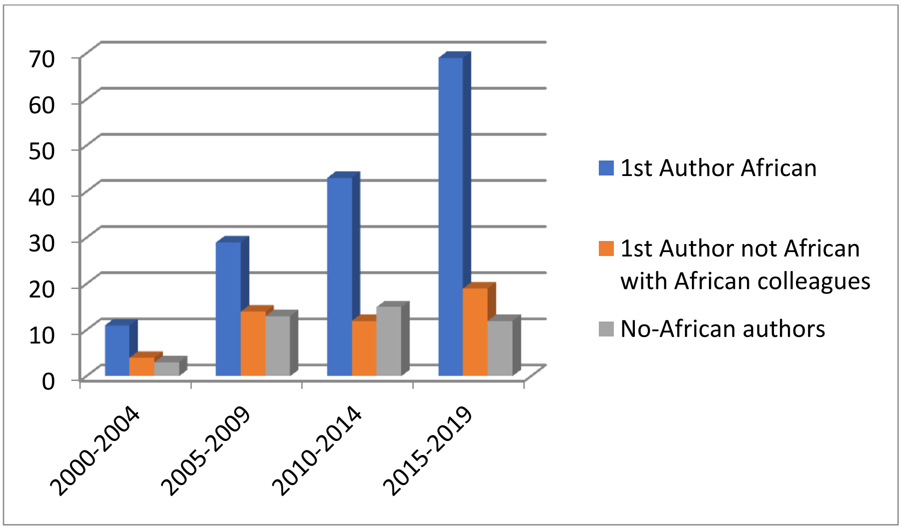

Figure 3.10. Number of scientific papers with a scientist from an African institution as first author versus those with first author not from an African institution.

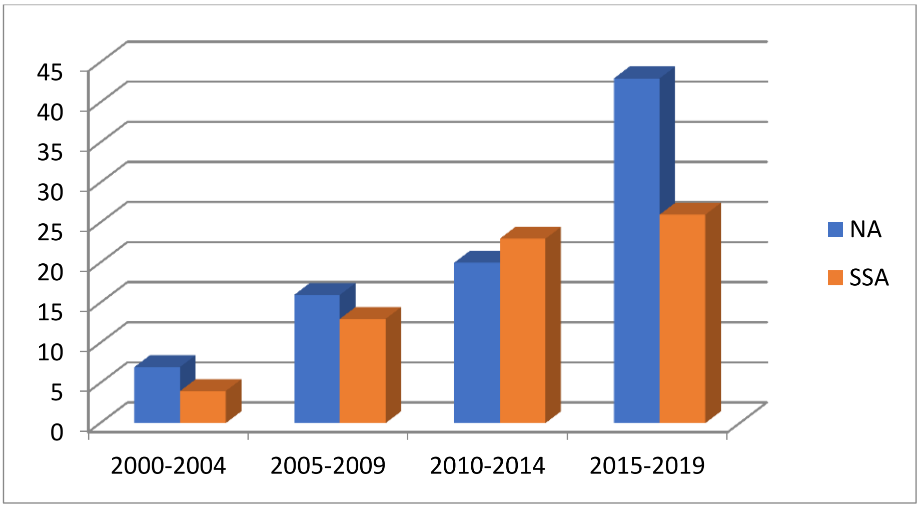

Figure 3.11. Number of scientific papers with a scientist from an African institution as first author on studies performed in NA vs. SSA.

For what concern the use of Graphical User Interfaces, Figures 3.15 and 3.16 show the diffusion of the most popular GUIs in NA and SSA respectively. Although the number of papers in which the GUI used to perform the study was not specified is quite high, we may notice that the most popular GUIs are GMS and Visual MODFLOW. The noticeable difference between NA and SSA is the use of PMWIN in the first, and the appearance in the last lustrum of the free GUI ModelMuse. From the information gathered, we can truly say that the panorama is still largely dominated by the use of commercial GUIs.

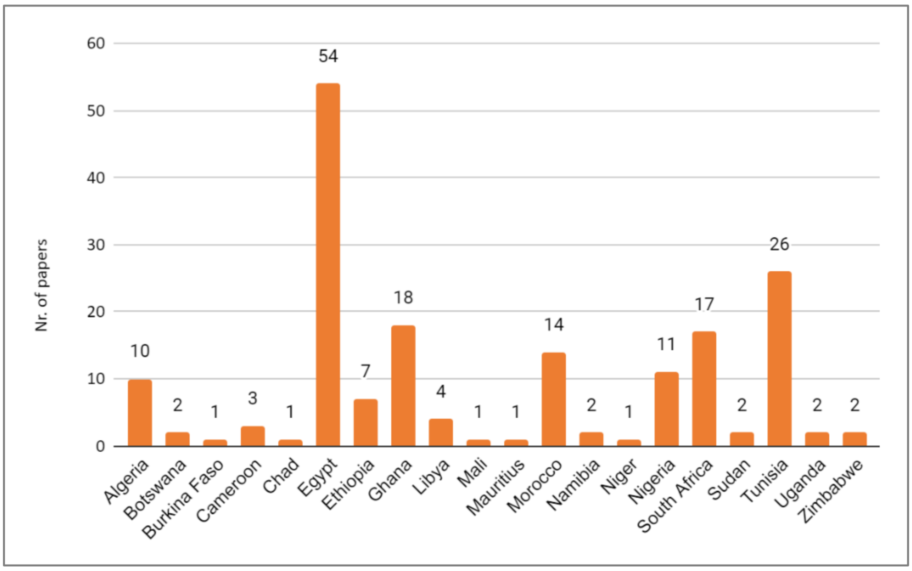

Figure 3.12. Scientific papers with African first Author divided per Country.

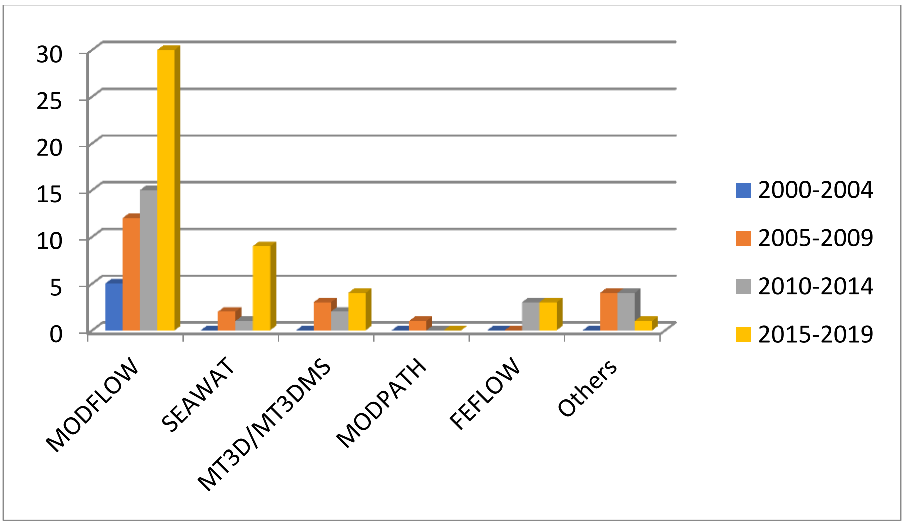

Figure 3.13. Codes used in scientific papers with a scientist from an African institution as first author published on studies performed in NA.

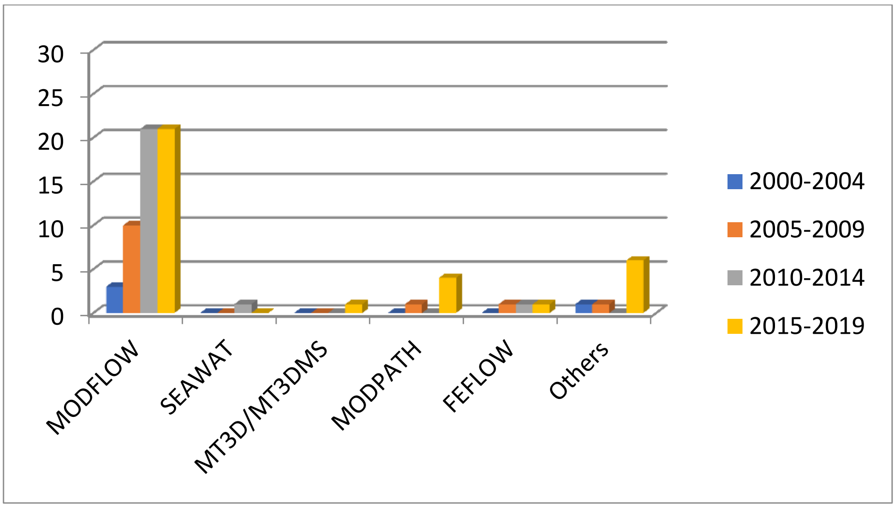

Figure 3.14. Codes used in scientific papers with a scientist from an African institution as first author published on studies performed in SSA.

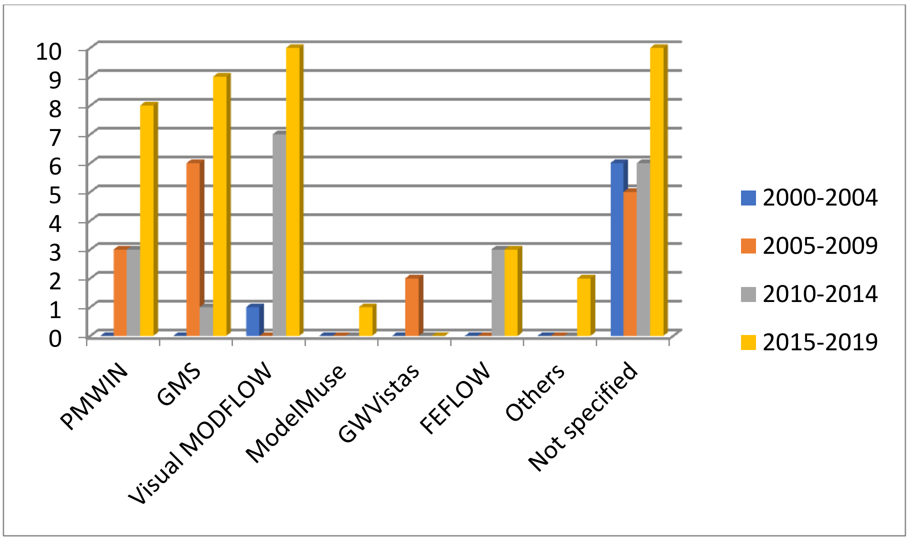

Figure 3.15. GUIs for groundwater numerical modelling used in scientific papers with 1st author from an African institution on studies in NA.

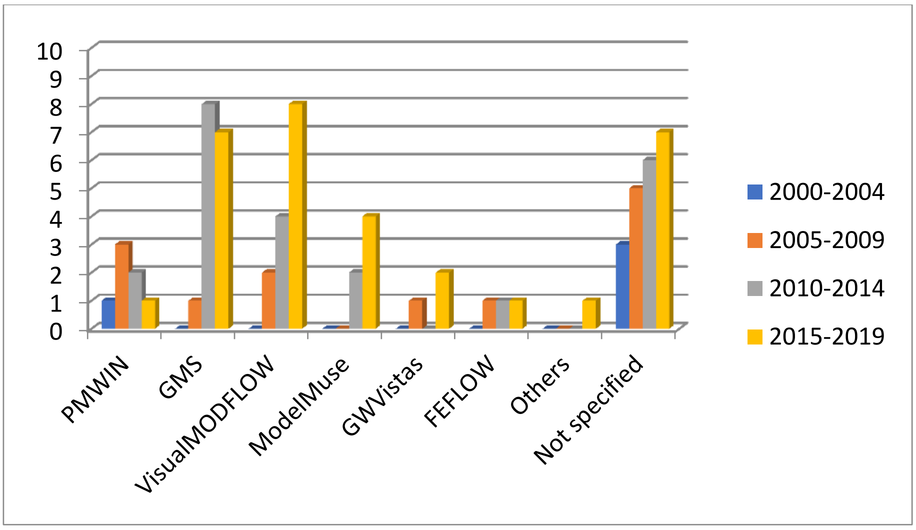

Figure 3.16. GUIs for groundwater numerical modelling used in scientific papers with 1st author from an African institution on studies in SSA.

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4. A survey on the use of digital tools for groundwater resource management in the African continent

Much of groundwater-related research in Africa has been driven by overseas organizations (Xu et al. 2019), and we also saw in the previous section that 38% of the research n modelling studies has been led by researchers non-affiliated to African Institutions. In order to get the view of African experts and to have a view on the present use of digital tools, we run a survey targeting African groundwater experts.

We structured a questionnaire in four sections with a total of 83 questions. The questionnaire was drafted in English and then translated in French. After circulating a first draft of the questionnaire among African colleagues, to test it and to get their view on potential missing parts, the questionnaire was finalised and translated also in French (folder annex_5). The first section (16 questions) aimed at characterising the respondent, while the second (30 questions) provided background information on the issues dealt. The third section provided information on groundwater monitoring and sampling practices (16 questions), while the fourth and last (21 questions) brought us into the perspective on the use of modelling and digital tools for groundwater resource management. An information sheet and Privacy Statement, according art. 13 D. Lgs. 196/2003 of the Italian legislation and article 13 UE Regulation n. 2016/679, was prepared as an introductory part of the questionnaire.

We retrieved more than 800 e mail addresses of African experts on groundwater modelling and also groundwater resource management throughout our contact network and by archiving the email addresses of the retrieved documents in the literature search. After validating these addresses, we submitted about 750 requests to compile the questionnaire in a dedicate web form. E mails were sent at least three times to each of the addresses kindly asking to fill in the survey. In some cases (countries with low rate of responses) additional efforts were undertaken. We received about 230 completed questionnaires; these were validated and only the questionnaires from experts having declared in the survey their area of expertise was related to groundwater management were finally retained for the analysis. We ended up with 220 completed questionnaires to be included in the analysis.

In the following section we report the main findings out of the questionnaire.

4.1 Results of the survey.

The 220 completed and analysed questionnaires were compiled from experts dealing with digital tools in groundwater resource management pertaining to 175 institutions from 41 African countries. Out of our sample, 82% of the respondents were male and 18% female; Figure 4.1 shows the percentage related to the academic degree of the respondents, which appears to be quite high, as 66% of the sample declares to have a PhD. Figure 4.2 presents the type of institutions involved in the survey and in Figure 4.3 the role of the respondents in their respective institution is presented. Figure 4.4 the answers per country. Barely 78%

of the respondents came from Academic or Research institutions, while the remaining 22% is mostly composed by water authorities (governmental, local or river basin authorities). About 90% of the interviewed declared to use digital tools for groundwater resource management daily. Given the African context and the main outcomes of the literature review, where most of the retrieved papers are dealing with research dedicated to applied issues (even when dedicated to understanding the hydrology of a system), the term "groundwater resource management" is intended here either as applied research to solve practical management problems (i.e. seawater intrusion, groundwater exploration or development, etc.) or as activities dedicated to true management of the resource (i.e. well licencing, exploration permitting, groundwater allocation, and so on).

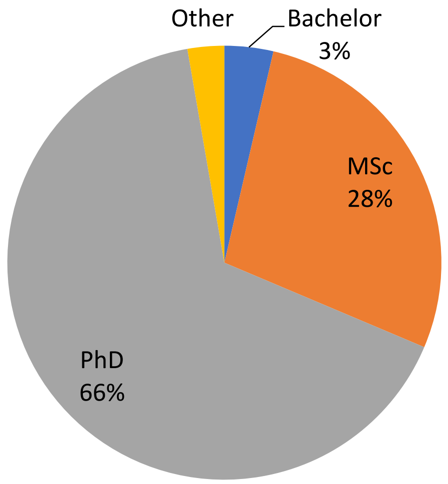

Figure 4.1. Type of academic degree and related percentage of the respondents.

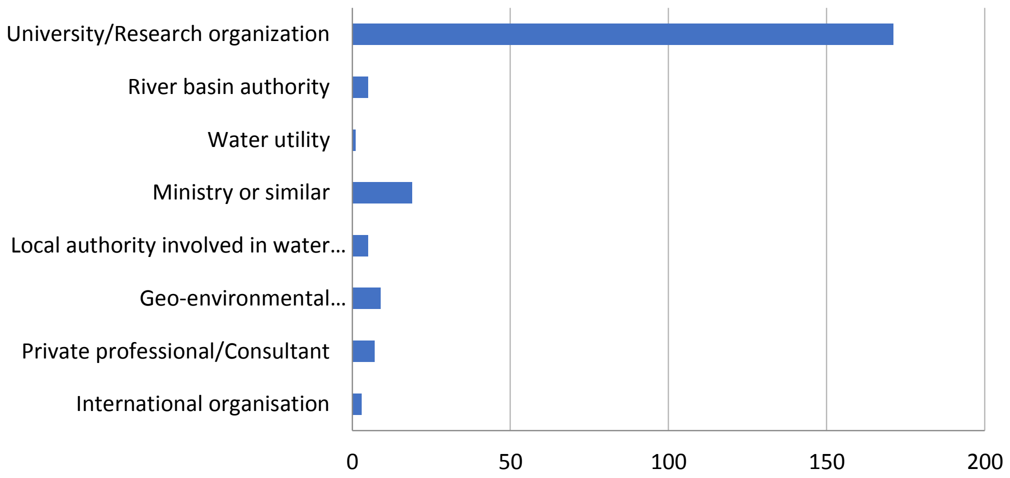

Figure 4.2. Type and number of institutions involved in the survey.

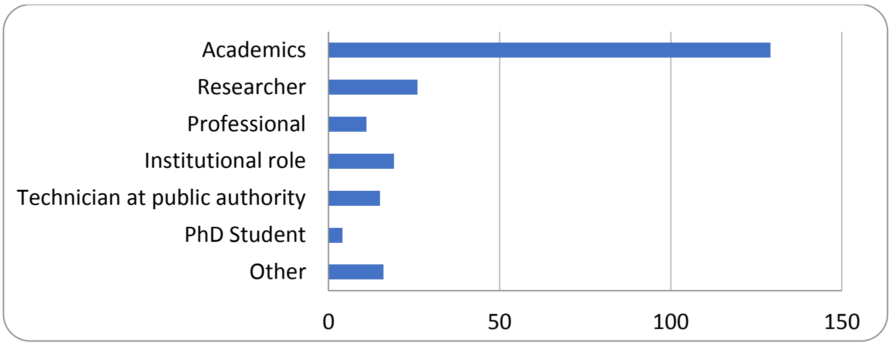

Figure 4.3. Roles of the respondents.

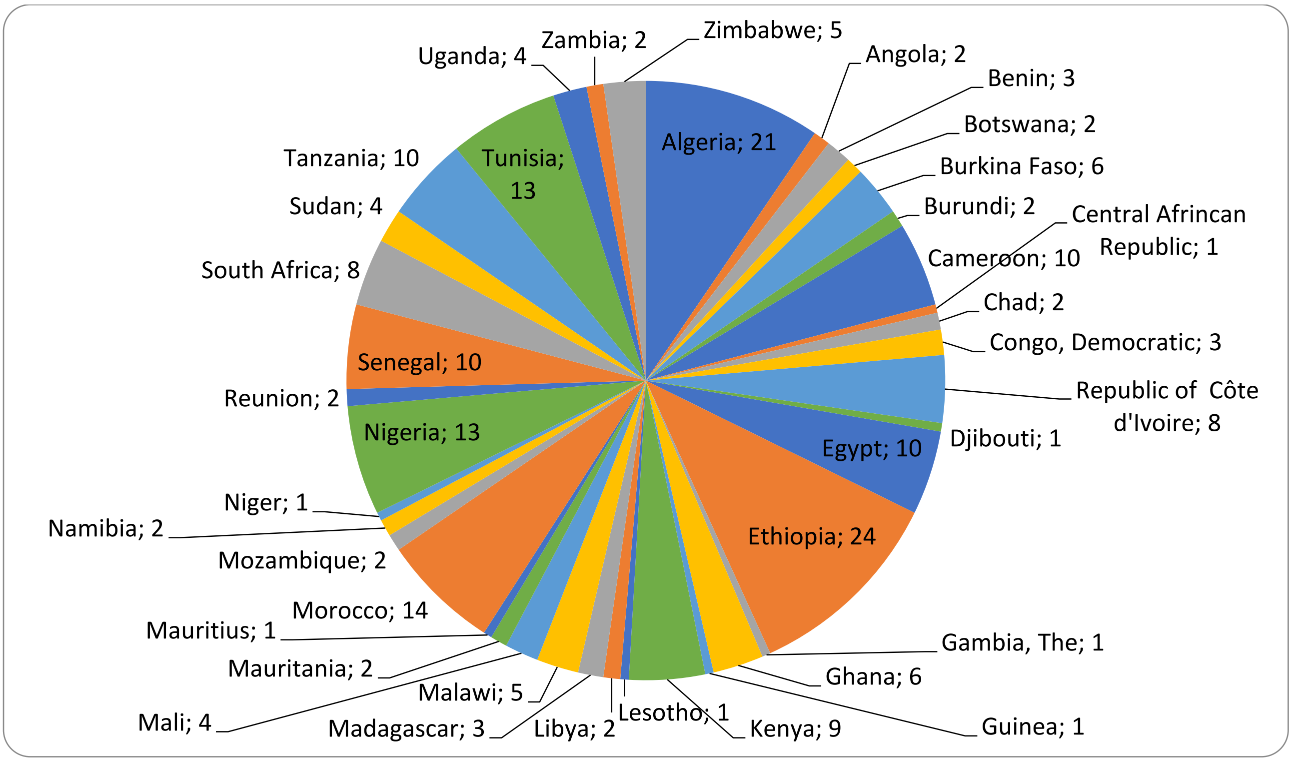

Figure 4.4. Number of answers per country.

Furthermore, 94% of the sample declared that his/her area of expertise is related to groundwater modelling or groundwater data analysis. Figure 4.5 reports the main areas of interest within groundwater resource management of the respondents; the interviewed are mostly involved in groundwater exploration, integrated water resource management and water quality issues.

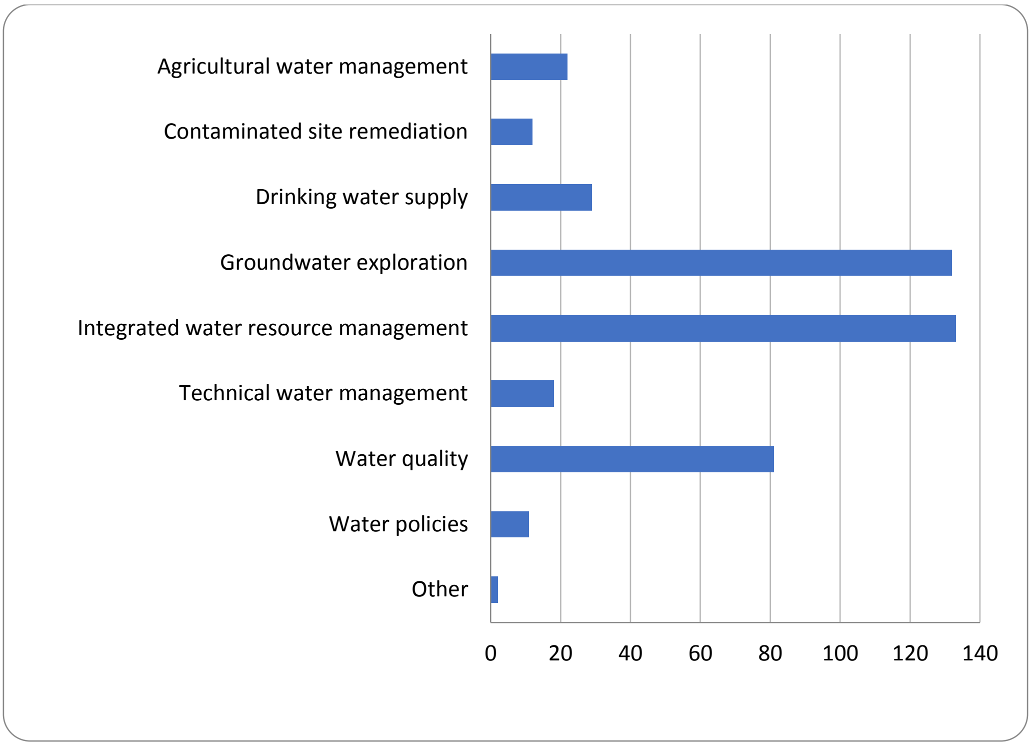

Figure 4.5. Areas of interest within groundwater resource management of the respondents (number of answers, each respondent selected two items).

In the first section of the questionnaire, we finally asked to self-evaluate their grade of expertise related to the use of GIS, groundwater numerical modelling and digital tools for statistics. Results are presented in Figure 4.6. On the high side of the proposed scale (values 3 to 5) the order of expertise is GIS, groundwater numerical modelling, and finally digital tools for statistics.

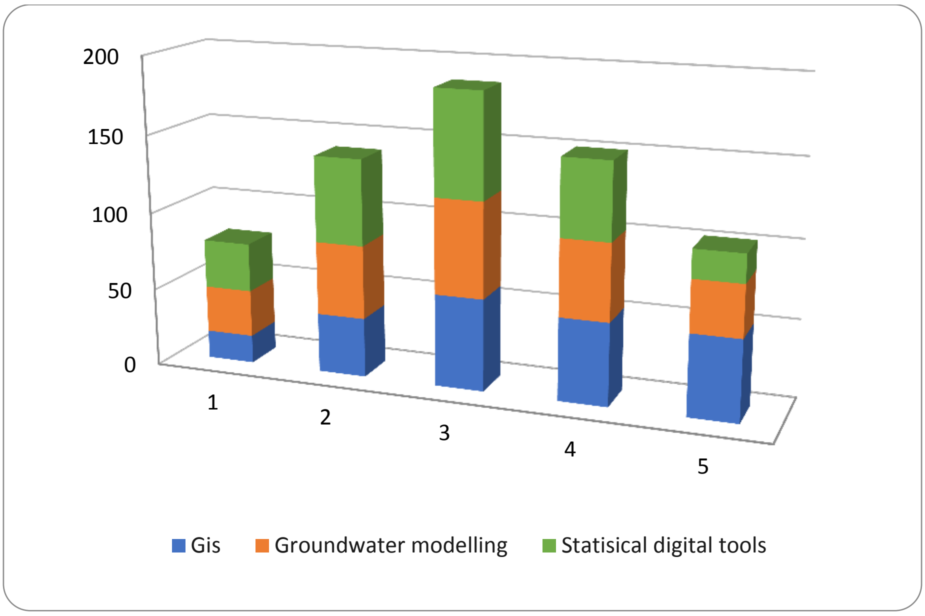

Figure 4.6. Self-evaluation on the level of expertise (1= low, 5= high) on the use of GIS, groundwater numerical modelling and digital tools for statistics.

Figure 4.7 shows the daily level of usage in percentage (0-100% on x axis) for the respondents (in % on y axis) of Calculation spreadsheet, GIS, Numerical modelling software, and software for advanced statistical analysis. This is quite high for calculation spreadsheets and GIS, but rather low for the tools for advanced statistical analysis.

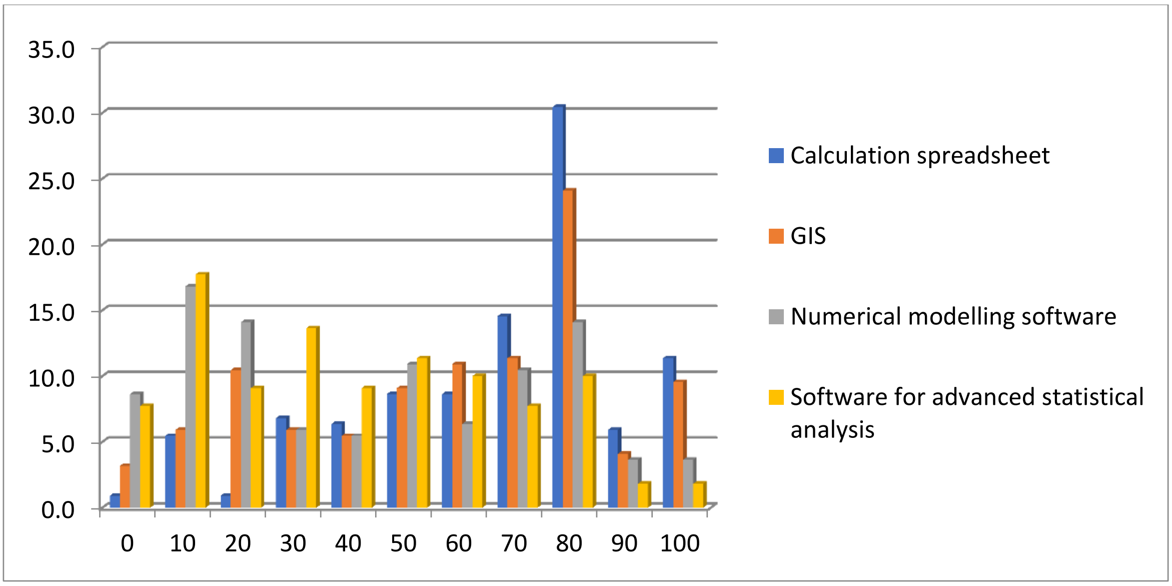

Figure 4.7. Daily level of usage in percentage (0-100% on x axys) for percentage of the respondents (on y axis) of Calculation spreadsheet, GIS, Numerical modelling software, and software for advanced statistical analysis.

The following Figures 4.8, 4.9, 4.10, 4.11 show the most common GIS application, modelling codes and related graphical user interfaces, and programming languages (three answers were possible) respectively used at the interviewed institutions. From the survey, we have a broader picture than that resulting from the literature review. The most used digital tools for groundwater resource management are obviously calculation spreadsheets, then GIS applications, followed by numerical modelling tools (with these being used approximatively at a 50% rate than the first tools) and finally advanced tools for statistical analyses. In the institutions interviewed, about 85% have at least one expert in GIS (with ArcGIS being the most diffused application, 97%, followed by QGIS, 77%). 63% of the institutions have at least one expert in groundwater numerical modelling, with 50% having also at least one person able to deal with contaminant transport. Most groundwater modelling applications are commercial ones (Visual MODFLOW, followed by AquaChem, GMS, FEFLOW, and PMWIN). The first mentioned open source modelling suites are FREEWAT and MODELMUSE – all in all the two do not arrive at 10% of the interviewed declared usage. From the literature review we notice that the code most used is MODFLOW, followed by FEFLOW, achieving the same conclusions we got through this survey. In 61% of the interviewed institutions there is at least one programming experts, being C/C++, Python and Java Script the most used languages.

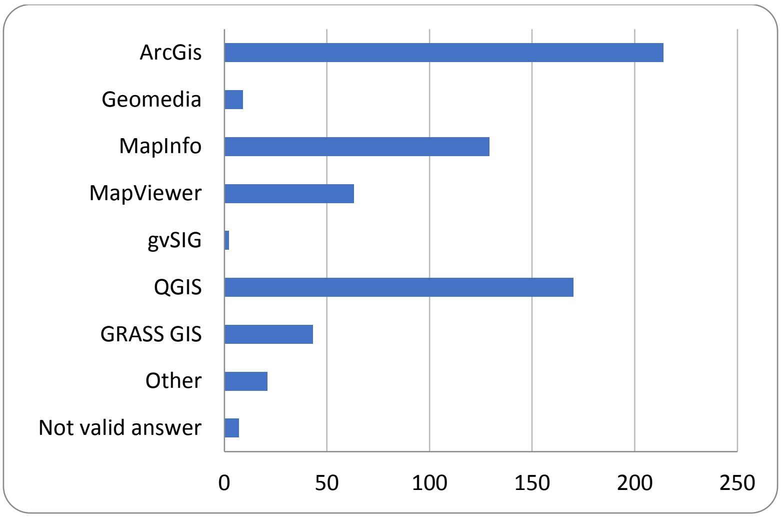

Figure 4.8. Most used GIS applications in the interviewed institutions.

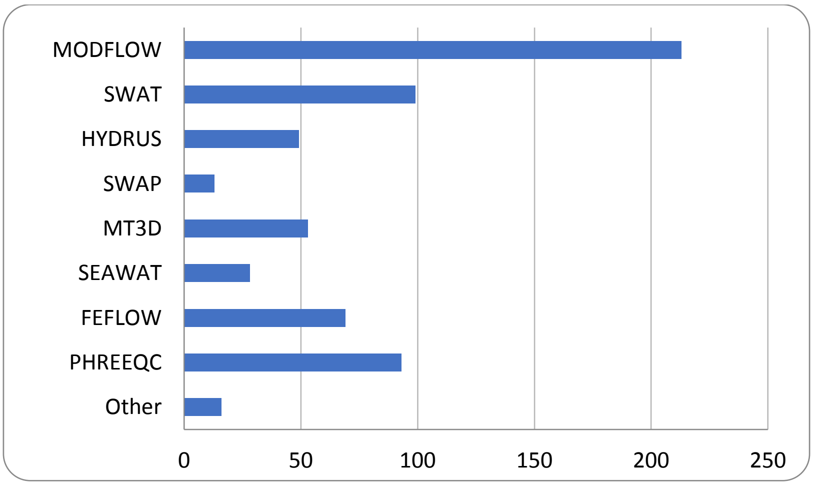

Figure 4.9. Most used numerical codes for groundwater modelling in the interviewed institutions.

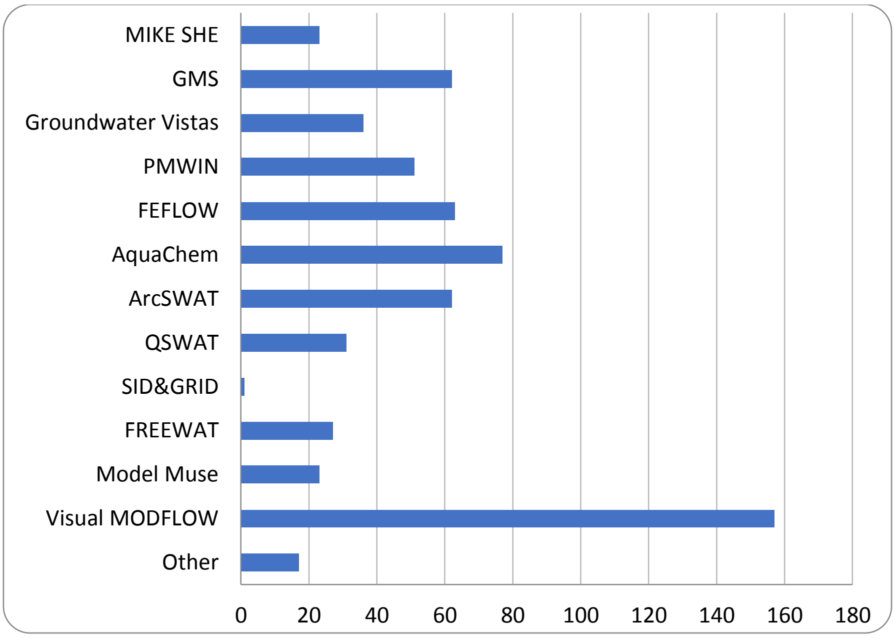

Figure 4.10. Most used GUIs for groundwater modelling in the interviewed institutions.

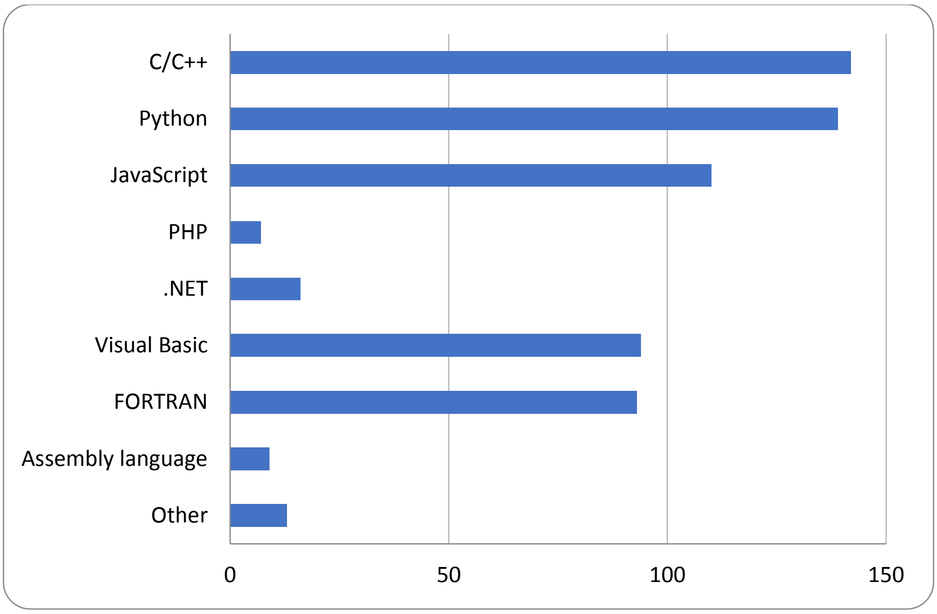

Figure 4.11. Most used programming languages for groundwater resource management in the interviewed institutions.

Unfortunately, when asked about the average computational capacity at their institutions, the respondents did not provide useful replies, with only 5% of the answers stating that satisfactory computational capacities are available, while 81% of the respondents declared they cannot answer, and another 14% did not provided a valid answer.

Most of the respondents (68%) do not know how many groundwater flow numerical models were implemented in their own country in the last ten years, and 50% of the sample also replied the use of groundwater numerical models is deemed to be an occasional activity, mostly applied for large engineering projects (33%), such as damming, surface water diversion, planning of new well fields. Only 10% of the sample states these tools are used on routinely base at their institution. Once built and used for a specific issue, these models are not updated regularly (45%), or even abandoned (32%), meaning they are not regularly used for groundwater use planning and management.

Figure 4.12 shows the purposes for which the respondents are using tools for numerical modelling in groundwater resource management (two answers per respondents). The most recognised application is limited to the analysis of the groundwater flow in aquifers. This topic was reformulated in another question to better specify why they use numerical modelling tools. According to the respondents these tools are mostly used with the objective of achieving sustainable groundwater management, hydrodynamic and hydrochemical characterisation of groundwater bodies, defining most productive areas of aquifers, and also managing the impact of climate extremes (floods and droughts).

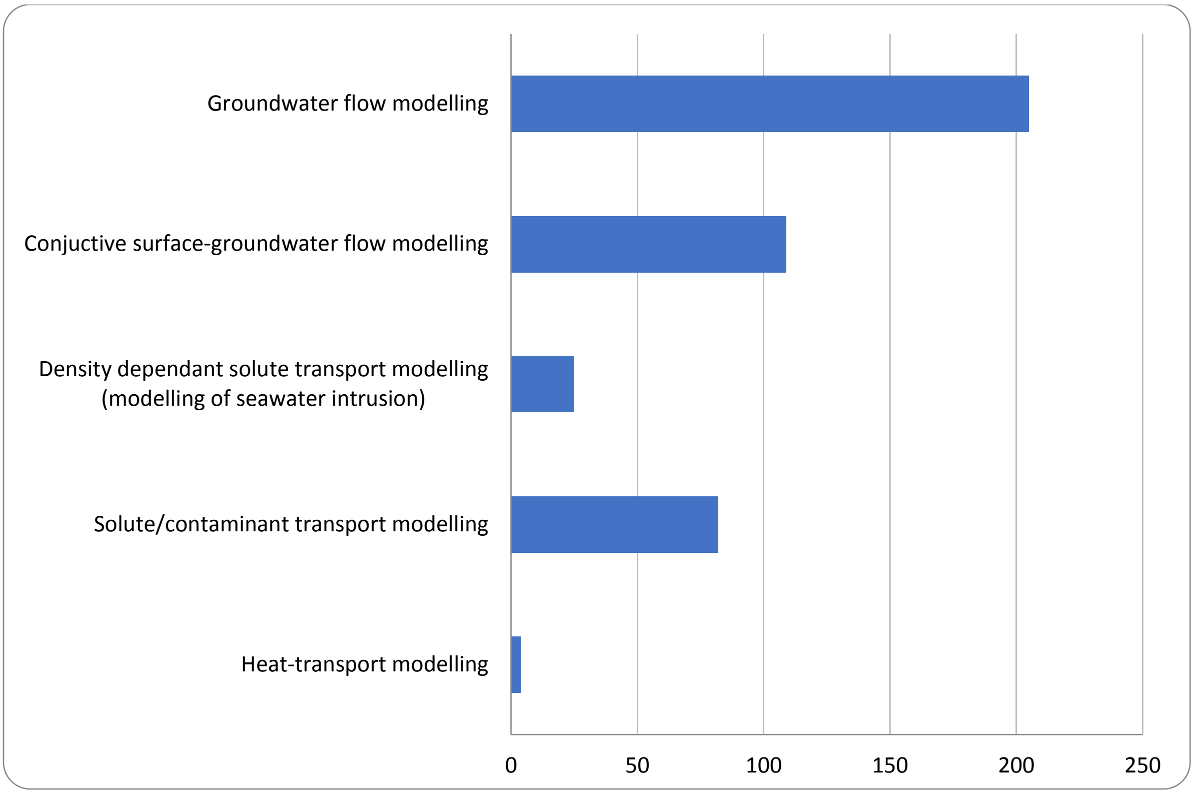

Figure 4.12. Purposes for using numerical modelling in groundwater resource management.

Digital tools such as groundwater flow numerical modelling are recognised as needed tools for groundwater resource management at national or regional level in African countries by about 60% of our sample, while only 10% believes adequate importance is not given to these tools. It is relevant to mention that about 30% of the interviewed declares they do not have a clear opinion about it. When asked to provide their opinion on the sectors where digital tools are currently used in their own country (two answers each; Figure 4.13), respondents believe groundwater numerical modelling and/or other digital tools are mostly used in the academic/research environment for research purposes (43%), while 30% of the respondents believe these tools are well-tailored for use in professional work. Still emerging is the usage in public authorities (14%). Only 22% of the respondents consider that on average skills and capacities for dealing with groundwater management using digital tools are available in the country, while it is the opinion of 50% that these are not reached. As far as the need for capacity building on the use of digital tools for groundwater management this is extremely high for 60% and high for 35%. Undertaking cooperative international research projects is considered the most relevant action to create capacity on digital tools, followed by training and national projects. Recruitment of a temporary expert to create capacity is thought to be less relevant.

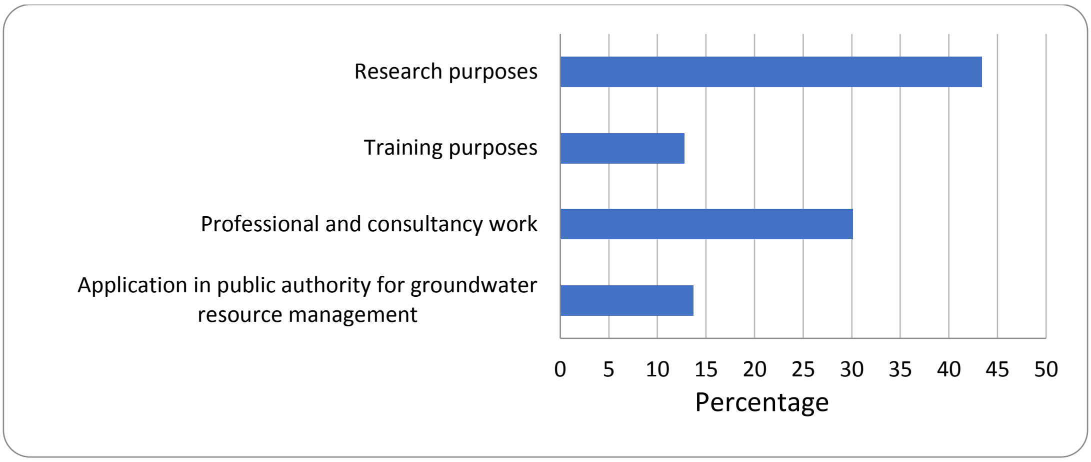

Figure 4.13. Opinion on the spreading in different sectors of digital tools.

On a scale from 1 (low) to 5 (high) digital tools are believed to improve groundwater resource management (Figure 4.14; % of preferences in y axis) as they may first support data-based decision making. Secondly, they may help the design of engineering projects (including land contamination and remediation), provide support for planning adaptation measures to climate change and also increase the value of data gathered at monitoring networks.

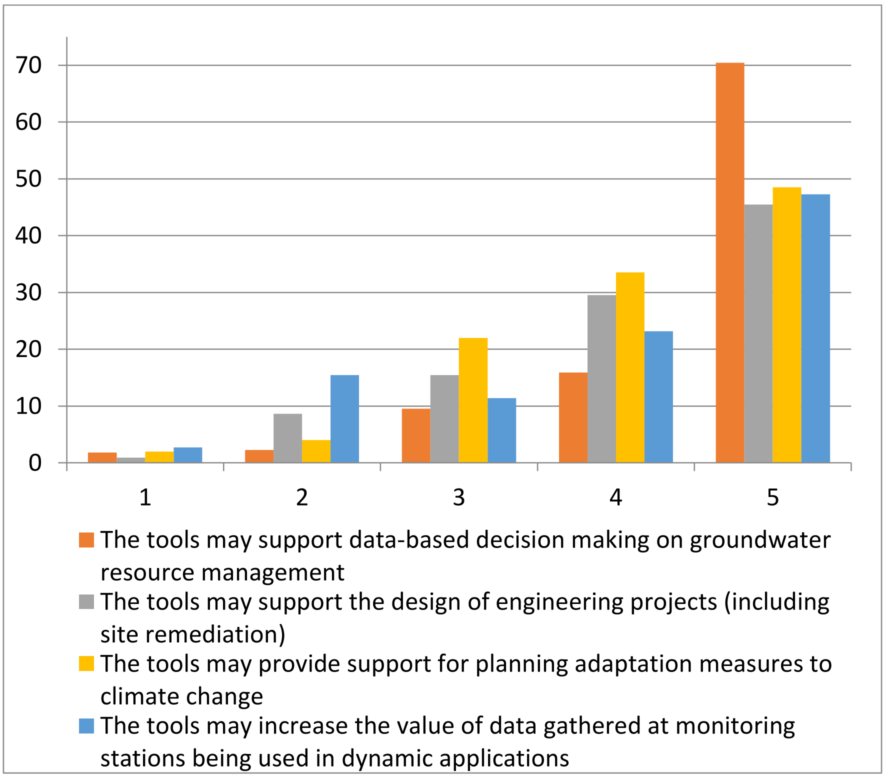

Figure 4.14. Main aim for using digital tools in groundwater resource management (% of preferences in y axis).

When talking about specific training needs (two answers each; Figure 4.15), 70% of the respondents believe that numerical modelling of groundwater flow and solute transport in aquifers is a first priority, followed by the use of software's for advanced statistical data analysis and presentation. Still the need for capacity on applied hydrogeology and hydrochemistry is seen as a need by 35% of the respondents, at a same rate than needs of training on monitoring skill (i.e. development and set-up of sensor networks).

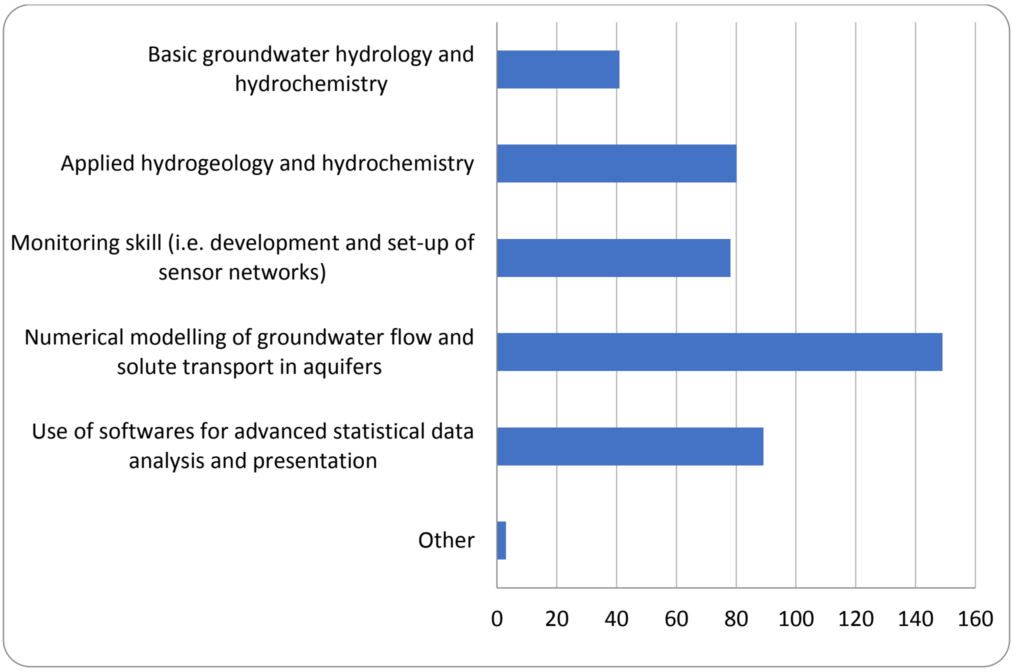

Figure 4.15. Areas in which capacity building is most needed for groundwater resource management.

In the context of the COVID pandemic, we posed a question on remote on-line training being as valuable as classroom training: 52% replied positively, while 41% believes remote training is not as valuable as class room training.

Asked about the knowledge of the term open source software 89% positively replied while 11% did not. A large part of the interviewed prefers open source software (71%), to commercial ones (22%). Those choosing open source software prefer it because of the possibility of developing tailored applications thanks to the code availability, software reliability and easy to use. Those responding that commercial software is better say this because they believe the software is more reliable and because of the quality of the support provided by the vendor and users' community. However, 95% of the respondents says they will be using digital/modelling tools if licences would be free. Open source and free software would be used if adequate training would be provided by 70% of the respondents, but a further 30% would require also support in the software use.

76% of our statistical sample agree on the fact that groundwater models, even built with scarce data, are valuable tools to drive hydrogeological investigations and to get initial insights on spatially distributed resource availability. On the importance of data gathering and simulation models, 52% of all the respondents are convinced that prior to any modelling exercise starts a robust data collection effort should be undertaken. It is interesting noticing that when looking at the Sub-Saharan English dataset, compared to the French one, 60% of the respondents would start simulations models even in data scarce environments because a model is a dynamic tool that can be improved with time, while only 23% of the French sample believe this.

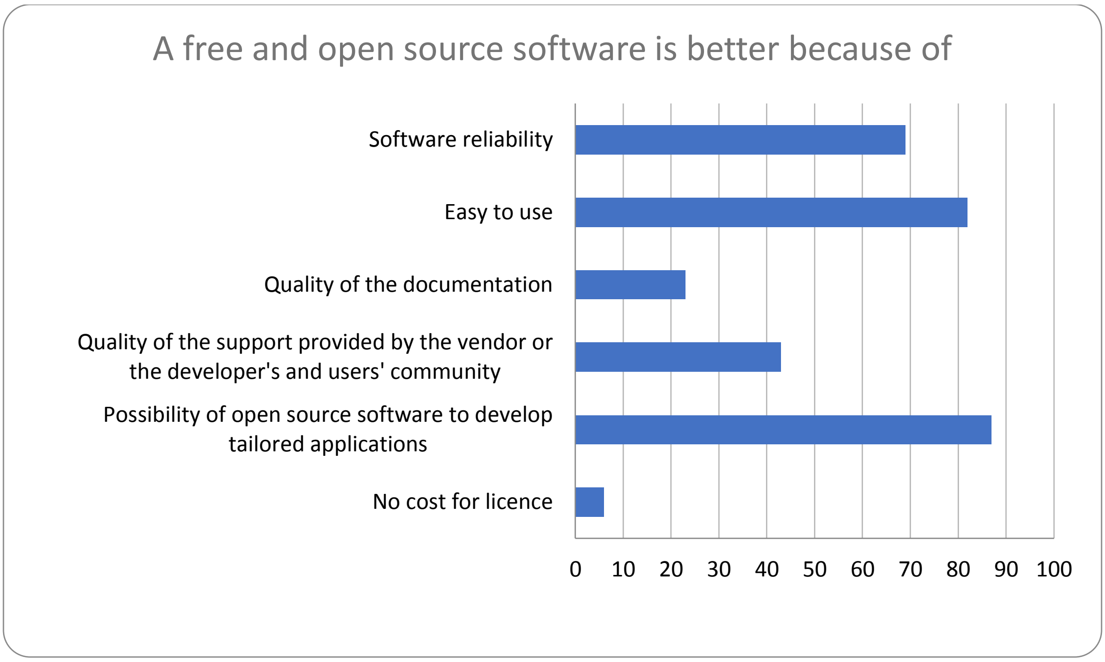

Figure 4.16. Reasons for preferring open source software (number of answers per item).

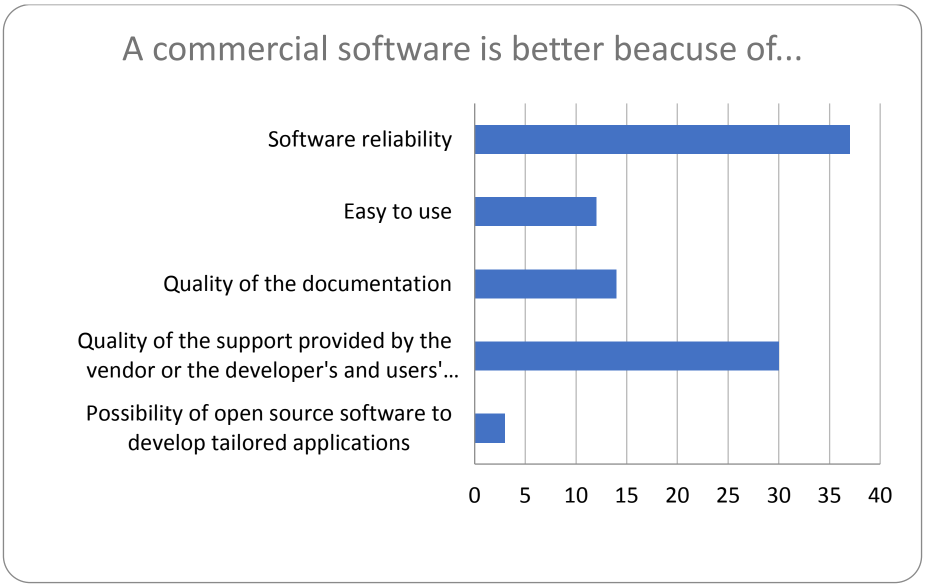

Figure 4.17. Reasons for preferring commercial software (number of answers per item).

The three key elements identified as barriers in the use of digital tools are: i) scarcity of data to develop a model, ii) inadequate financial resources to develop and maintain a model, and iii) missing capacities (Figure 4.18). On another view, main problems in developing groundwater models are related to data scarcity, lack of computing skills, and lack of computing resources (Figure 4.19). In this sense, 67% of the respondents declared that sufficient data to build models are available only in few areas of their country. In fact, only about 50% of the respondents declared that digital archive of groundwater-related data exists in their country.

Finally, the lack of adequate and well-functioning web connections (Internet) is considered the main bottleneck in favouring the spread of new technologies.

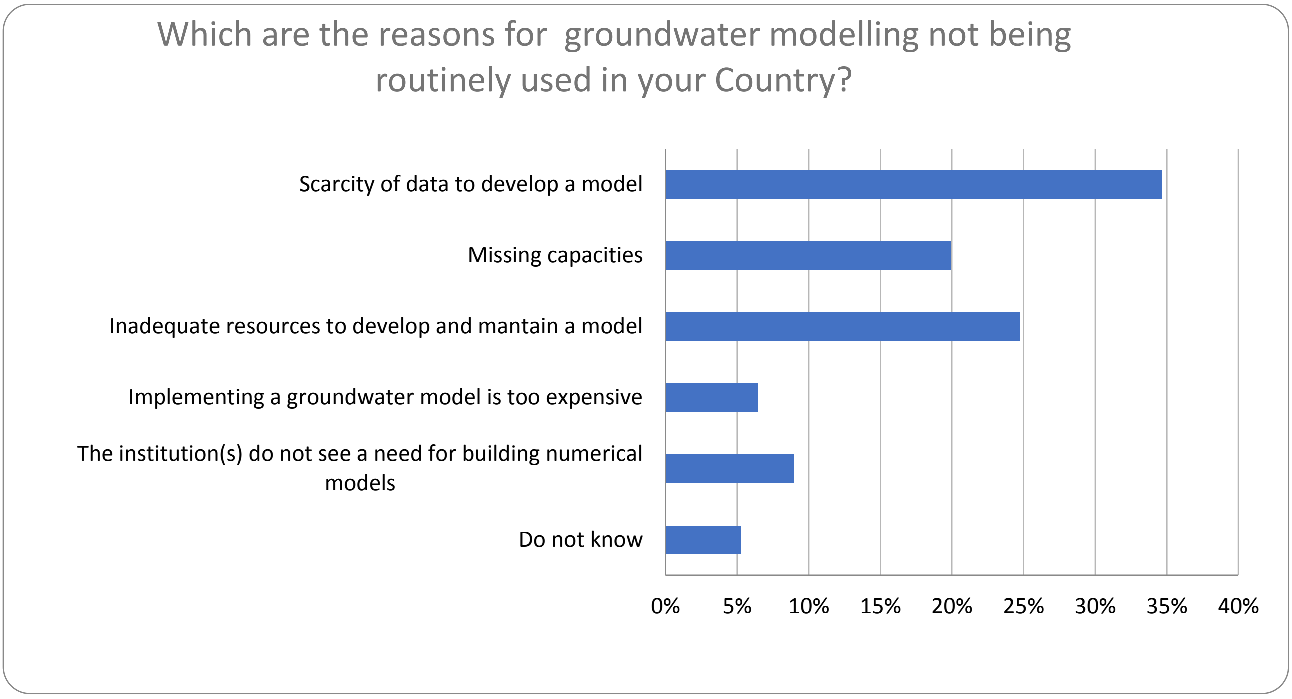

Figure 4.18. Reasons for groundwater modelling not being routinely used (percentage of answers per item).

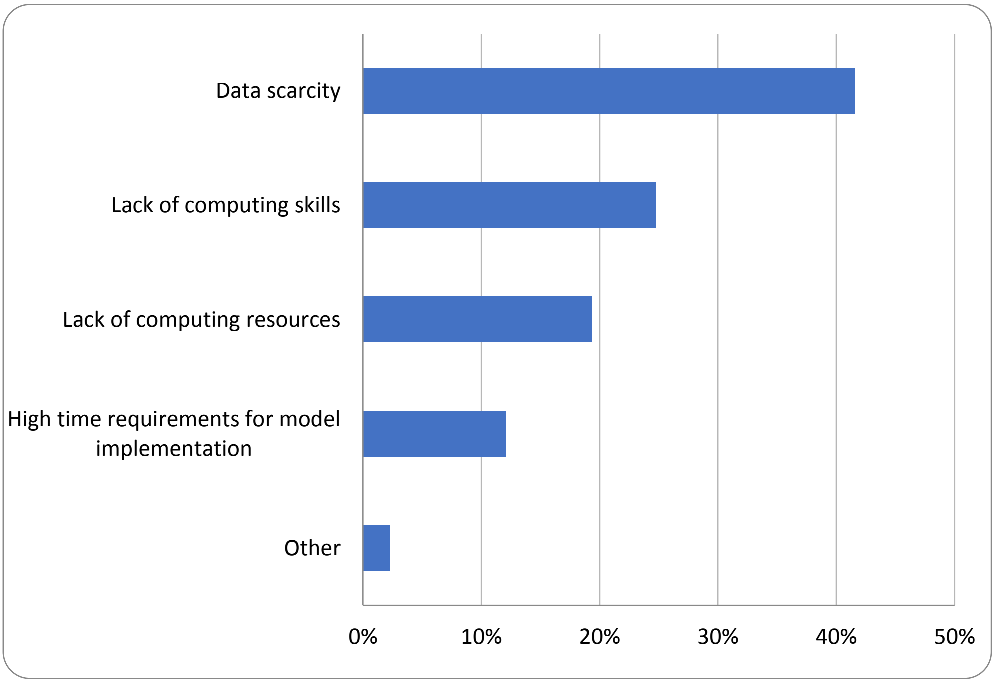

Figure 4.19. Main problems encountered in implementing groundwater models (percentage of answers per item).

5. Discussion and Conclusions

Groundwater is a critical resource for people and ecosystems. Digital tools may support and boost efficient data management so that more technically sound and even community-based decisions may be made. In this view, development and diffusion of robust open source and free software constitutes a cornerstone to enhance groundwater management, thus empowering as much as possible technical units in water authorities, academia and private companies, also in communities/countries with limited resources. Commercial proprietary software has been traditionally used to such scope, but the cost is usually prohibitive in many ow-income areas of the world. Using open source software (codes and GUIs) may nowadays constitute a valid alternative and may also help by saving money and redirecting funds locally for creating quality jobs for the young people.

The activities run addressed the need for having an updated state-of-the-art overview on the use of software and digital tools for sustainable groundwater management in the African continent. The results of the research allow a clear view on the present level of knowledge and on the diffusion of such tools.

From the analyses of the documents retrieved during the literature review, it is clear that groundwater modelling studies increased in Africa in the last 20 years (2000-2019) and this increasing trend is still ongoing in 2020. This is particularly true when analysing the scientific papers where scientists affiliated to an African Institution are listed as first authors. In this case, we assume that the first author has been either performed the bulk of the research or has been leading the research. This analysis is needed as a considerable number of studies (38%) has been led (in 2000-2019) by scientists non-affiliated to African Institutions. To this regard, the African led papers increased about six times, passing from 11, for the period 2000-2004, to 69 in the period 2015-2019. However, we noticed a sharp divide between North Africa (NA) and Sub-Saharan Africa (SSA), as in NA five countries barely contributed to the whole scientific production on the topic in about the same amount than 40 countries. African led studies are mostly run in Egypt, Ghana, Tunisia, South Africa, Morocco, Niger, Nigeria and Algeria.

We then analysed the codes for numerical modelling used in the papers with an African first author in NA and in SSA: the most used code is MODFLOW, which is a free and open source (OS) USGS code. The only noticeable difference between NA and SSA is related to the use in NA of codes to be coupled to MODFLOW, that is MT3D and MT3DMS and SEAWAT (also free and open source codes), for the simulation of solute transport in aquifers and density-dependant problem. As these codes requires additional knowledge on groundwater hydrology and hydrochemistry, or contaminant hydrogeology, we may infer that potentially in NA these disciplines are more pronounced that, in general, in SSA countries.

The same issue was investigated through a the structured survey, to get an insight on the software currently used in public and private African institutions for groundwater management. The investigated sample comes mainly from the academic/research sector (about 78%) with a high academic degree (PhD for 66% of the respondents), and largely (90%) declared to use digital tools for groundwater resource management daily.

Furthermore, 94% of the sample declared that his/her area of expertise is related to groundwater modelling or groundwater data analysis, with main areas of interests related to groundwater exploration, integrated water resource management and water quality issues. The groundwater exploration prominence among the topics is characteristic for the African context. The respondents' digital skills are stronger first in GIS, then in numerical modelling and, finally, in the use of software for statistical analysis. Barely these technologies are listed in the same order concerning their daily use.

As per the GIS applications used, still ARCGIS ESRI application is the most common, but it is challenged by the free and open source QGIS and the commercial MapInfo GIS applications. Codes for groundwater flow simulations named by the respondents are basically coincident in the order of magnitude of use with those we retrieved by means of the literature review. A larger use of the FEFLOW code was detected and also of the PHREEQC. The latter was not identified clearly in the literature review. Out of the most used GUIs for numerical modelling, still it is confirmed what is retrieved by the literature review. The most used code is open source and free, but it is used by means of commercial proprietary interfaces. The usage of the two identified free and open source GUIs (ModelMuse and FREEWAT) is still far in number respect to the commercial ones.

Unfortunately, when asked about the average computational capacity at their institutions, the respondents did not provide useful replies, with only 5% of the answers stating that satisfactory computational capacities are available, while 81% of the respondents declared they cannot answer, and another 14% did not provided a valid answer.

Out of this data, we may say that the usage of digital tools, in this case numerical modelling, is still low. It seems that the approach followed in the last twenty years by the African groundwater community has been that of a simple user – while at least at the academic research level should be more looking at understanding the tool's functioning. The only example of active tool development is mentioned in [258] (see the *modelling_documents* file for details). In this paper, the authors detail the development of a tool, under ESRI ARCGIS, to facilitate the use of a database and the visualisation and management of spatial and temporal data related to the study of the Gareb-Bouareg aquifer (Morocco) This entitles the need for having teaching programming skills in order to get capacity in modifying and tailor open source codes. This would also allow to run sounding academic courses which in turn could be complemented with professional training.

A particular focus was dedicated to review the use of Open Source tools in groundwater-related data management, analysis and modelling, thus detailing the current status and future perspective, aiming at providing suggestions on potential robust and reliable available tools to be exploited. As said above, at present the digital groundwater management is still dominated by commercial applications. Anyway, the declared use of free and open source GIS applications (QGIS and GRASS GIS) and the appearance of free and open source GUIs for modelling (FREEWAT and ModelMuse) shed a light on an increasing trend (which is nowadays quite visible in Europe) of usage of these software. It can be considered a sign of attention towards the use of free and open source software in its entirety.

What is still contrasting with the use of free and open source codes such as MODFLOW, and related codes, is the large use of commercial proprietary GUIs such as GMS and Visual MODFLOW. That is, it seems the authors are not free to use the codes without a commercial GUI. A particular case is that of PMWIN, which was a free GUI at the beginning of 2000 and it is now commercial, but sold at a lower price than the previously mentioned interfaces. In some papers, the authors even made confusion between the codes for modelling and the graphical user interface (even in journals with good academic reputation), demonstrating also an acritical use of the software. Anyway, the fact the most used numerical code is open source (MODFLOW) will make it easier, to migrate from commercial to free and OS software.

A specific section of the questionnaire was dedicated to evaluate the diffusion and the willingness to adopt OS and free solutions in respect to commercial ones. Asked about the knowledge of the term open source software, 89% of the sample positively replied while 11% did not. A large part of the interviewed prefers open source software (71%), to commercial ones (22%). Those choosing open source software prefer it because of the possibility of developing tailored applications thanks to the code availability, software reliability and easy to use. Those responding that commercial software is better say this because they believe the software is more reliable and because of the quality of the support provided by the vendor and users' community. Of course, when talking about software reliability, each group of respondents may have its own reasons in calling it in favour of OS or commercial software. OS and free software would be used if adequate training would be provided by 70% of the respondents, but a further 30% would require also support in the software use.

The research run allowed a detailed overview of the usage and diffusion of software for groundwater resource management in Africa. Both the literature review and the survey run show that digital tools have entered and are progressing in the African context. This progress is however, faster in NA and scattered in SSA. For example, South Africa and Ghana seem to have created one or more focal centres for knowledge transfer on such tools operational use, while in other countries we do not have this evidence. It is clear that when comparing the retrieved number of scientific papers in SSA to that in NA, SSA countries have huge possibilities for improvement.

Digital tools such as groundwater flow numerical models are recognised as needed tools for groundwater resource management at national or regional level in African countries by about 60% of our sample, while only 10% believes adequate importance is not given to these tools. It is relevant to mention that about 30% of the interviewed declares they do not have a clear opinion on it. When asked to provide their opinion on the sectors where digital tools are currently used in their own country, respondents believe groundwater numerical modelling and/or other digital tools are mostly used in the academic/research environment for research purposes (43%), while 30% of the respondents believe these tools are well-tailored for use in professional work. Still emerging is the usage in public authorities (14%).

Most of the respondents (68%) do not know how many groundwater flow numerical models were implemented in their own country in the last ten years, and 50% of the sample also replied the use of groundwater numerical models is deemed to be an occasional activity, mostly applied for large engineering projects (33%), such as damming, surface water diversion, planning of new well fields. Only 10% of the sample states these tools are used on routinely base at their institution. Once built and used for a specific issue, these models are not updated regularly (45%), or even abandoned (32%), meaning they are not regularly used for groundwater use planning and management. For the respondents the most valuable application of modelling tools is limited to the analysis of the groundwater flow in aquifers. This topic was reformulated in another question to better specify why they use numerical modelling tools. According to the respondents, these tools are mostly used with the objective of achieving sustainable groundwater management, hydrodynamic and hydrochemical characterisation of groundwater bodies, defining most productive areas of aquifers, and also managing the impact of climate extremes (floods and droughts).

Digital tools are believed to improve groundwater resource management as they may first support data-based decision making. Secondly, they may help the design of engineering projects (including land contamination and remediation), provide support for planning adaptation measures to climate change and also increase the value of data gathered at monitoring networks. It is worth mentioning there are some countries (Senegal, South Africa, Egypt) where, although with limited scientific production, modelling tools are increasingly used in consulting services. In West Africa, this is particularly true for Senegal, where modelling technical reports have been produced to serve planning and management of groundwater supply to urban and rural areas.

A large part of our statistical sample (76%) agrees on the fact that groundwater models, even built with scarce data, are valuable tools to drive hydrogeological investigations and to get initial insights on spatially distributed resource availability. On the importance of data gathering and simulation models, 52% of all the respondents are convinced that, prior to any modelling exercise starts, a robust data collection effort should be undertaken. It is interesting noticing that when looking at the Sub-Saharan English dataset, compared to the French one, 60% of the respondents would start simulation models even in data scarce environments, being a model a dynamic tool that can be improved with time, while only 23% of the French sample believes this.

As far as capacity building needs, only 22% of the respondents consider that, on average, skills and capacities for dealing with groundwater management using digital tools are available in the country, while it is the opinion of 50% that these are not reached. As far as the need for capacity building on the use of digital tools for groundwater management this is extremely high for 60% and high for 35%. Undertaking cooperative international research projects is considered the most relevant action to create capacity, followed by training and national projects. Recruitment of a temporary expert to create capacity is thought to be less relevant. When talking about specific training needs, 70% of the respondents believe that creating capacity on use of numerical modelling tools in aquifers is a first priority, followed by the use of software for advanced statistical data analysis and presentation. Still capacity on applied hydrogeology and hydrochemistry is seen as a need by 35% of the respondents, at a same rate than training on monitoring skill (i.e. development and set-up of sensor networks). This is made evident from the conclusions, i.e., of the project “*Gestion intégrée et concertée des ressources en eau des systèmes aquifères d’Iullemeden, Taoudéni Tanezrouft et du fleuve Niger «GICRESAIT*" where training on modelling was recommended, along with creation of capacity on GIS, spatial database, and, of course, acquisition of new data. In the context of the COVID pandemic, 52% of our sample believes remote training is as valuable as class room training, but not the 41%.

The three key elements identified as barriers in the use of digital tools are: i) scarcity of data, ii) inadequate financial resources to develop and maintain a model, and iii) missing capacities. On another view, main problems in developing groundwater models are related to data scarcity, lack of computing skills, and lack of computing resources. In this sense, 67% of the respondents declared that sufficient data to build models are available only in few areas of their country. In fact, only about 50% of the respondents declared that digital archive of groundwater-related data exists in their country. Finally, the lack of adequate and well-functioning data transmission networks (Internet) is considered the main bottleneck against the spread of new technologies.

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APPENDIX A

The following tables explain the data shown in the graphs in Section 3.

Decade	Lustrum	Total
Document count per year		
2000-2009	2000-2004	31
	2005-2009	79
2010-2020	2010-2014	94
	2015-2019	152
	2020	38

Table A1. Number of documents divided per year intervals.

Decade	Lustrum	Total
SSA document count per year		
2000-2009	2000-2004	17
	2005-2009	54
2010-2020	2010-2014	59
	2015-2019	87
	2020	16
NA document count per year		
2000-2009	2000-2004	17
	2005-2009	28
2010-2020	2010-2014	41
	2015-2019	77
	2020	23

Table A2. Number of documents regarding NA and SSA Countries, divided per year intervals.

Decade	Lustrum	Total
Paper count per year		
2000-2009	2000-2004	18
	2005-2009	56
2010-2020	2010-2014	70
	2015-2019	100
	2020	36

Table A3. Number of papers divided per year intervals

Decade	Lustrum	Total
SSA paper count per year		
2000-2009	2000-2004	6
	2005-2009	34
2010-2020	2010-2014	39
	2015-2019	47
	2020	15
NA paper count per year		
2000-2009	2000-2004	12
	2005-2009	22
2010-2020	2010-2014	31
	2015-2019	53
	2020	21

Table A4. Number of papers regarding NA and SSA Countries, divided per year intervals.

Code	Nr. of papers
MODFLOW	216
SEAWAT	21
FeFlow	16
MT3D/MT3DMS	16
MODPATH	7
HYDRUS-1D	3
Other used twice*	12
Other used once**	26
Unknown	5

Table A5. Number of papers found per Code used for the simulations.

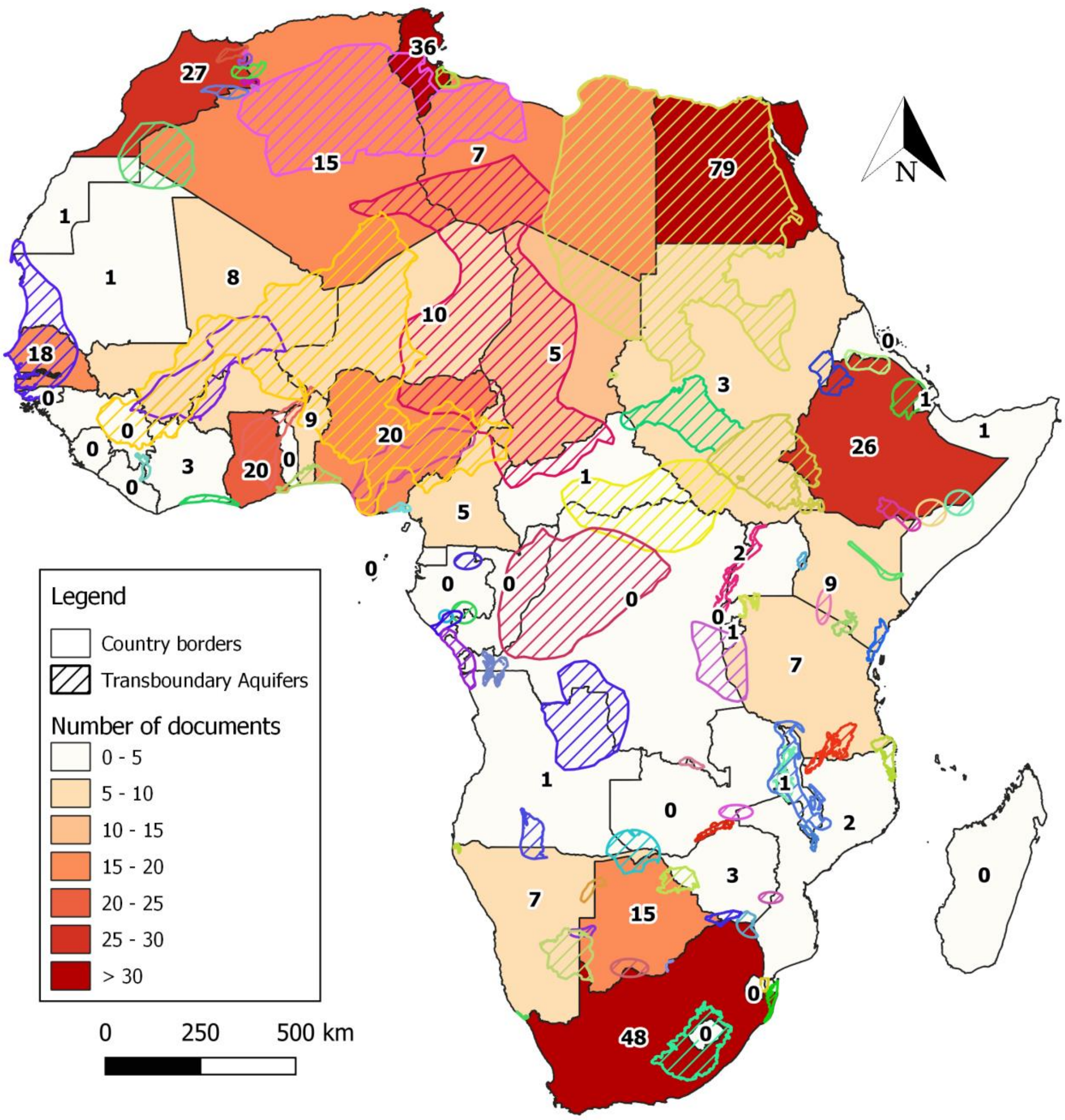
*Used twice: FEMWATER, GroundWater, MicroFEM, MIKE-SHE, TRIWACO, WEAP
**Used only once: CODESA-3D, GARDENIA, GEMFLOW, HydroGeoSphere, Hysuf-FEM, iMOD, MARTHE, MODCOU, FEN, CORE2DV4, HYDROS, MOGA, PMPATH, Wetspass, NETPATH, OpenGeoSys, PHAST 1.2, ps2D, d3f, SPRING, SUTRA, SUTRA2D, TOUGH2, WINFLOW, WINTRAN, YAGmod.

Code	**nr. papers**
MODFLOW	110
SEAWAT	8
FeFlow	6
MODPATH	5
Other used twice*	4
Other used once**	17
Unknown	4

Table A6. Number of papers found regarding SSA Countries, divided per Code used for the simulations. *Used twice: HYDRUS-1D, MIKE-SHE.
**Used only once: FEMWATER, GARDENIA, GEMFLOW, HydroGeoSphere, MARTHE, HYDROS, PMPATH, MT3D/MT3DMS, OpenGeoSys, PHAST 1.2, ps2D, d3f, SPRING, SUTRA, WINFLOW

APPENDIX B

Number of retrieved documents per country.



APPENDIX C

C1. Groundwater Modelling in the Senegalo-Mauritanian basin

The onshore transboundary Senegalo-Mauritanian Basin (SMB; including Mauritania, Senegal, Gambia, Guinea Bissau and Western Sahara) is the largest of the northwest African Atlantic margin basins. It covers roughly more than 300 000 km^2 (IAEA 2017). The IAEA-supported project RAF/7/011 (IAEA 2017) was the first attempt for solving common hydrogeological questions, and the related report well synthesizes the main characteristics and problems of this transboundary system. Figures C1 and C2 provide an overview of the Mauritanian and Senegalese main hydrogeological features of the SMB.

Three main aquifer systems providing exploitable groundwater resources can be distinguished in the SMB (Madioune et al., 2016). They are:

1) the shallow aquifer systems (Quaternary and Continental Terminal) discontinuously cover the whole sedimentary SMB. It is dominantly made of sand and sandy clay, which vary in proportion across its extent. The aquifers are intergranular, and the best groundwater potential occurs in sand layers. It comprises the following aquifers:

- in Senegal: infrabasaltic (occurs below basalts), Thiaroye, Littoral Nord, alluvial, Continental Terminal and Oligo-Miocene aquifers;

- in Mauritania: Boulanouar (3,000 km^2), Bennichab (1,200 km^2) and Trarza (20,000 km^2) aquifers.

- the alluvial aquifer on the both sides of the Senegal River in the two countries.

This aquifer system overlies the more consolidated deposits of the Eocene, Palaeocene, and the Maastrichtian. The Shallow aquifer system ranges between 0 to 150 m thick, with a water table depth between a few metres to a depth of 72.5 m.
Nitrate contamination is known to occur in certain places.

2) the intermediate aquifer system includes Eocene and Palaeocene formations, and mainly comprises limestone, often karstic. The Eocene aquifer is exploited in the central western part of Senegal and along the Senegal River. The Palaeocene aquifer occurs mainly in western Senegal, around Pout. These aquifers constitute one of the main sources of drinking water for Dakar. The Intermediate aquifer system ranges between 40 to 120 m thick, with a water table depth between a few metres to 102.5 metres depth.

3) The deeper aquifer system, mainly of Maastrichtian age (Kane et al., 2012), extends across the whole of the SMB and generally consists of sand, sandy-clay and calcareous sandstone. Groundwater storage and flow are largely intergranular. This aquifer constitutes the main source of groundwater supply in Senegal. It is a transboundary system, but it is not exploited in Mauritania due to low hydraulic conductivity and high salinity. The deeper aquifer system is about 250 m thick, with a water table depth between a few metres to 140 metres. Typical borehole depth varies between 25 and 680 m. It is typically highly productive, although aquifer properties vary according to local characteristics (lithology,

thickness, etc.). Except for the Eastern and Western borders, the aquifer is generally confined.

Recharge occurs from direct rainfall and indirectly from rivers, and is estimated at about 103x 10^6 m³/y to the Maastrichtian deeper aquifer system. It is mainly recharged in the Western part in the Diass horst where formations outcrop, and at the contact with the basement formations and the unconsolidated formations in the South-Eastern part of Senegal.

High iron, fluoride and salinity are seen in the Central Western part of Senegal, saline intrusion in the coastal areas.

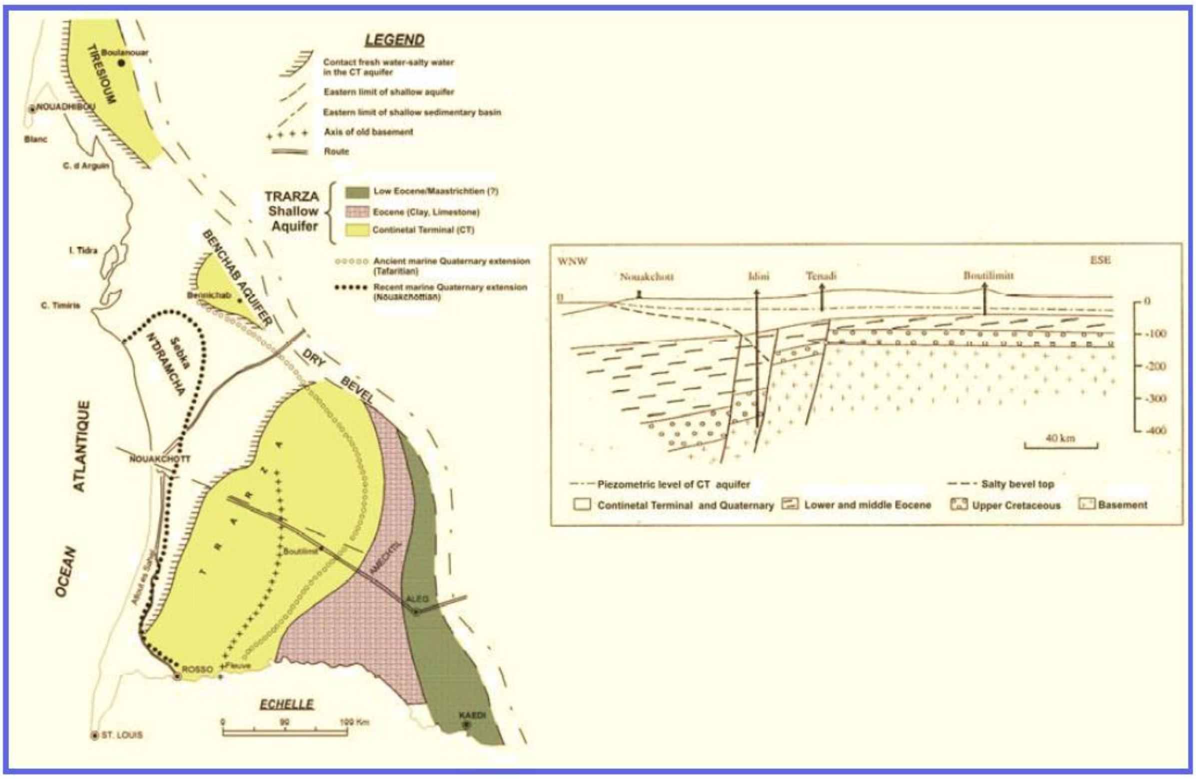


Figure C1. Hydrogeological map of the Mauritanian part of the SMB and SSW/WNW cross section (from IAEA 2017).

Further information on the hydrogeology of the SMB may be found for each single state at the Africa Groundwater Atlas.

The IAEA study concludes mentioning an urgent need for modelling the Maastricthian aquifer (the main challenge for water supply in the future in Senegal) as a whole, considering palaeo-hydrological aspects, to assure a suitable groundwater management in the future. Similarly, in Mauritania, the quantification of the available resources of the Trarza and Brakna aquifers via modelling tools is deemed a fundamental requirement for ensuring a sustainable water supply.

In the SMB, based on this survey, the totality of the modelling efforts have been performed in Senegal (Fig. C3) and halted at the state boundaries. We did not retrieve any modelling study run in the Mauritanian side, Gambia, Guinea Bissau and Western Sahara. At the end of an expert panel held in Geneve in 2019 (Willemin, 2019) it was acknowledged the need to further develop knowledge of the SMB, in particular in Guinea Bissau and The Gambia, to produce predictive models.

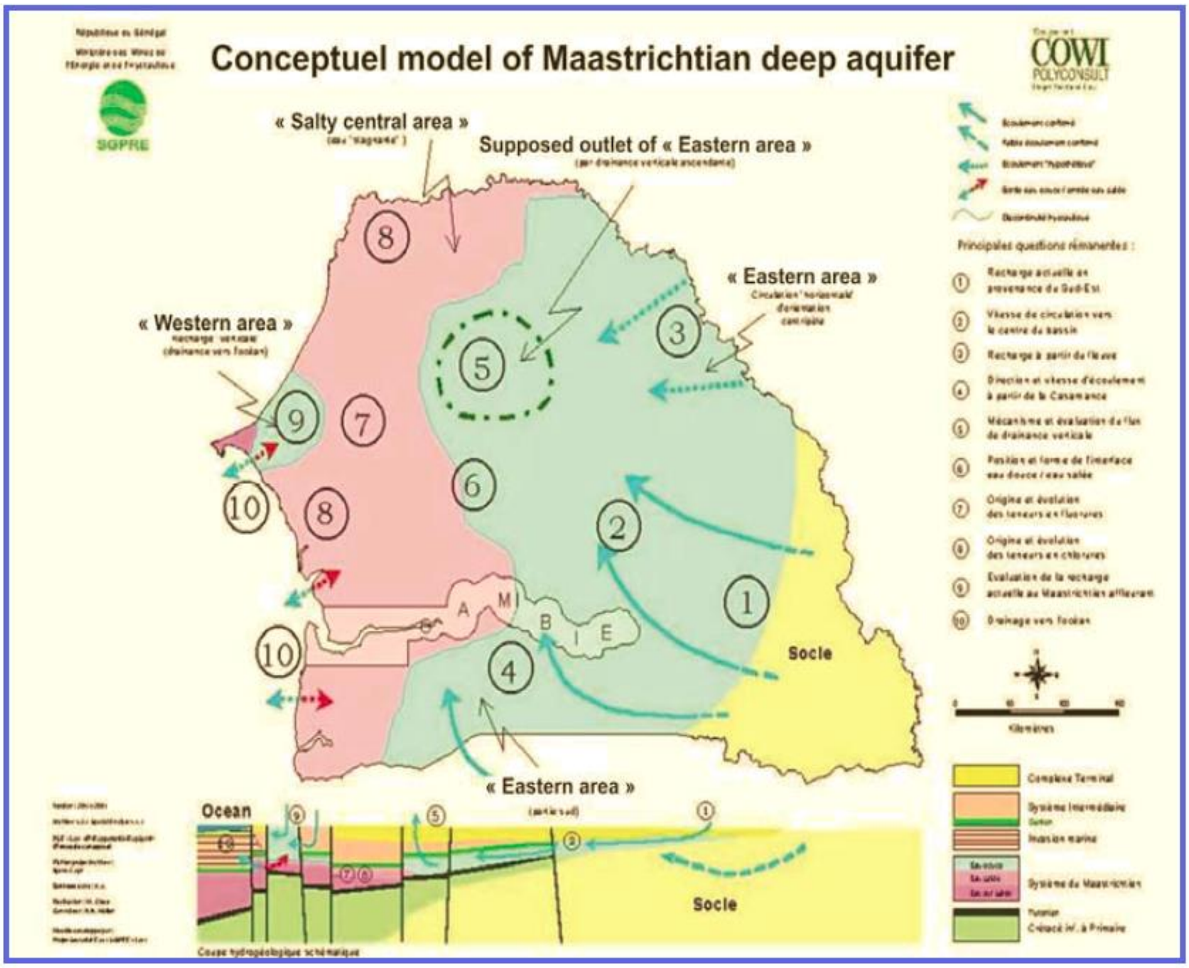


Figure C2. Hydrogeological map and deep aquifer conceptual model in the Senegalese part of the SMB (from IAEA 2017).

1.1 Groundwater modelling efforts in Senegal

The spatial distribution and the list of modelling efforts retrieved for the Senegalo-Mauritanian Basin are presented in Figure C3 and Table C1 respectively. For the detailed information on the models the reader is referred to Annex 1. We retrieved all in all 18 modelling studies (scientific papers (5), conference proceedings (1), technical reports (4), PhD and MSc thesis (3 and 5 respectively)). These studies, when dealing with spatially distributed problems were conducted using mostly the MODFLOW code (except two cases, one with FEFLOW and one with Cast3M). HYDRUS 2D and SUTRA were used to exemplify research questions at local 2D cross sectional scale. The HYDRUS code was used in four studies dealing with local research topics in one dimension. Aside from what is presented in one scientific paper, simple distributed modelling applications are generally shown (most of the models are 1 layer) and little or no information is provided on the calibration process. Nine studies are related to groundwater management (evaluating seawater intrusion, assessing potential areas for withdrawal, assessing groundwater supply for sustainable mining activities) while five have purely descriptive hydrological objectives (i.e. increasing understanding on the system hydrodynamics or evaluating the impact of climate change on groundwater). One study (led by non-Senegalese) is about the application of groundwater modelling for paleobotany/paleoclimatic studies in the Niayes area. Nearly all studies (13) are led by Senegalese authors. The spatial relevance of the modelling efforts varies from local (6) to sub-regional (7). The areas most interested by the modelling activities (Figure 1) are the northern coastal aquifers, the Dakar region and the horst of Diass (being the place where the aquifers are mostly recharged by direct rainfall), and the Saloum and Casamance hydrological systems in the mid and southern part of the country.

In the following paragraphs a brief summary of the contents of the retrieved studies is presented.

In the northern part of Senegal, in [357] a basic and initial groundwater flow numerical model was produced to analyse the impact of the irrigation and to prepare a streamlined model of the very salty alluvial aquifer of the Delta of the Senegal River. Still in the Senegal Delta area hydrodynamic simulation dealing with soil salinization linked to evaporative processes were performed. In particular, [409] collected and further analysed by means of a 1D HYDRUS model data on the physical characterization of soils and the water table from the point of view of the exchanges between the irrigation water and the shallow and very salty water table in the rice cropping area of Savoigne. In [410] a similar topic is dealt with a 2D model in the same area to characterize the interactions between groundwater and surface water (rivers, including irrigation water and drainage water). The simulations confirmed the dominant role of the evaporative recovery and groundwater rising on the risks of salt accumulation in the soil surface. On the contrary, agricultural practices did not seem to have any substantial long-term impact on the risk of salinization. The solution of deep groundwater drainage, tested in the developed model demonstrated to be a feasible option to reduce the risk of salinization.

The sandy Quaternary and the deep Maastrichtian aquifers located in the northern coastal zone of Senegal, from the locality of Kayar in the south to Saint-Louis in the north, constitute the main sources of water supply for urban and agricultural needs as well as mining activities [363]. The quaternary sands aquifer of the northern littoral (stretching from the Senegal basin into the Saloum river basin) knew during the last decades excessive pumping for drinking water supply of Dakar city and its suburbs. This overexploitation generates a high drawdown of the whole aquifer. Dissolved salts are the main contaminants in the groundwater of the area combined with those due to the invasion of salt water, caused mainly by economic activities related to industry and irrigation as well as domestic ones.

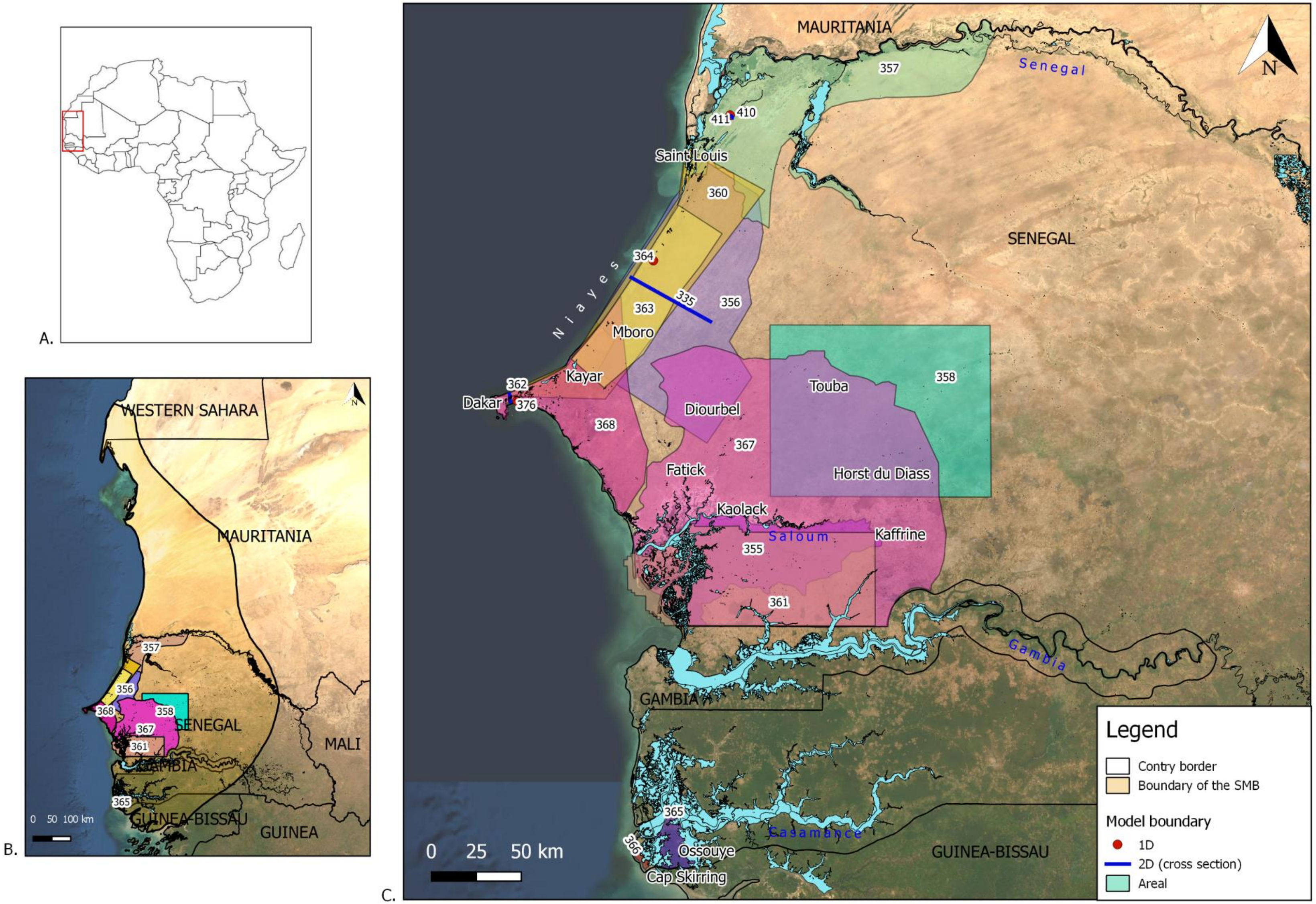


Figure C3. Boundary of the Senegalo–Mauritanian Basin, location and extension of the retrieved modelled areas.

ID	Year	Document Type	Objective short	Country	Model name	Main investigated aquifer	Watershed	Code used for simulation
335	2019	Research paper	Seawater intrusion	Senegal	Niayes area	Quaternary sand aquifer	Saloum	MARTHE
355	2002	PhD Thesis	Understanding hydrology	Senegal	Saloum hydrologic system	Continental terminal	Saloum	MODFLOW
356	2002	MSc Thesis	Groundwater management	Senegal	Niayes area	Niayes aquifer	Senegal	MODFLOW-96
357	2005	MSc Thesis	Groundwater management	Senegal	Delta of the Senegal river	Coastal aquifer	Senegal	MODFLOW
358	2006	MSc Thesis	Groundwater management	Senegal	Touba	Maastrichtiaan aquifer	Saloum	MODFLOW
359	2017	PhD Thesis	Understanding hydrology	Senegal	Horst of Diass	Paloecene/Maastrichtian	Saloum	Not specified
360	2012	MSc Thesis	Understanding hydrology	Senegal	Quaternary sands aquifer of the northern littoral	Quaternary sands aquifer of the northern littoral	Senegal/Saloum	MODFLOW
361	2014	Research paper	Understanding hydrology	Senegal	Saloum aquifer	Continental Terminal	Saloum	MODFLOW
362	2012	Conference proceeding	Understanding hydrology	Senegal	Quaternary sands aquifer of the northern littoral	Quaternary sands aquifer of the northern littoral	Senegal/Saloum	SUTRA v.2.1
363	2018	Research paper	Groundwater management	Senegal	Quaternary sands aquifer of the Dakar peninsula	Quaternary sands aquifer of the northern littoral	Senegal/Saloum	FEFLOW
364	2016	Research paper	Groundwater management	Senegal	Niayes area	Niayes aquifer	Saloum	HYDRUS-1D
365	2017	Technical report	Groundwater management	Senegal	Plateau of Oussouye	Continental terminal	Casamance	MODFLOW
366	2017	Technical report	Groundwater management	Senegal	Cap Skiring	Maastricthian/Continental Terminal	Casamance	MODFLOW
367	2018	Technical report	Groundwater management	Senegal	Arachidier basin	Upper aquifers (Quaternaire/Continental terminal et Oligo-miocène) and intermediate (Éocène/ Paléocène)	Saloum/Gambia	MODFLOW
368	2018	Technical report	Groundwater management	Senegal	Horst of Diass	Paleoecene/Maastrichtian	Saloum	MODFLOW
376	2020	Research paper	Understanding hydrology	Senegal	Dakar region	Quaternary sandy formation	Saloum	HYDRUS-1D
410	2015	PhD Thesis	Understanding hydrology	Senegal	Senegal River Delta	Superficial aquifer	Senegal	HYDRUS-2D
411	2006	MSc Thesis	Understanding hydrology	Senegal	Delta of the Senegal river	Coastal aquifer	Senegal	HYDRUS 1D

Table C1. Table summary of the models retrieved for the Senegalo - Mauritanian Basin.

The development of a steady state numerical hydrodynamic modelling based on finite differences scheme [360], allowed characterizing the spatial distribution of aquifer permeability and recharge. It also made possible to calculate the various terms of the water budget. The production of an initial groundwater flow numerical model was also the main outcome of an MSc thesis [356] for the same area.

In the same area, a local groundwater flow numerical model was implemented to evaluate a water balance that enables the provision of a permanent water supply to a dredge pond for mining activities, whilst minimising the risk of flooding of the cropping depressions adjacent to the mine site or drying out of the farming wells [363].

In the coastal aquifer of the Niayes region, one of the most significant effects of spatially varying pumping from the aquifer of north littoral is the intensification of seawater intrusion. In [335] a cross-section numerical model for the areas close to Mboro was built. The main objective was that of simulating seawater intrusion in the aquifer under different management scenarios. The model was able to predict, with good accuracy, the movement and extension of salt water in the northern coastal aquifer. A 1D model was used in [411] to assess the risk of groundwater contamination following to the use of chemicals (fertilisers and pesticides) in the Niayes area.

The Dakar peninsula in Senegal is home to nearly 2.5 million people in an area of approximately 100 km^2 [362]. Formerly supplied with water from local underground resources, in particular the water table Quaternary sands, the city is now mostly served by a 300 km water pipe from Lake Guiers located in the Senegal River valley.

The management of the Quaternary sand aquifer nonetheless remains an environmental and health issue for the urban area, whose development strongly affects the groundwater regime and has the consequence of intensification of seasonal flooding in low-lying areas associated with major overflow septic tanks. Hydrogeological and geophysical investigations detailed in the highly urbanized area of Pikine specified the groundwater renewal regime and confirmed the significant increase in groundwater recharge due to wastewater infiltration in urban areas. This phenomena was investigated in [362] combining the use of geophysical methods and 2D cross sectional numerical simulations. Still in the Dakar area, a 1D research model [376] was implemented in order to use diurnal or seasonal water table fluctuation to estimate groundwater evapotranspiration at different land uses and climate conditions. The overall results indicate that higher evapotranspiration values were observed when the water table is shallow, suggesting that evapotranspiration is mainly driven by the water table depth at this site.

The Horst area of Diass system (Thies and Dakar regions) is characterized by the presence of large SONES collection centres for the water supply of Dakar and its surroundings and by an intense agricultural and industrial activity whose sources of water supply are scarce. In [368] a sub-regional numerical model was built (in a consultancy project) for the Horst de

Diass in order to improve the hydrogeological knowledge with a view to evaluating the potential of water resources and their optimal use for the drinking water supply in Dakar and its surroundings. The aim of the modelling activities was also to improve the management tools of the Directorate of Water Resources Management and Planning (DGPRE) by developing a mathematical model. The hydrogeological model of the Horst de Diass aquifer system confirmed the state of overexploitation of the Paleocene and Maastrichtian aquifers in the area. Given the simulated overexploitation, potentially brackish water may intrude in the aquifers along the coastline. The model demonstrated that pumping rate corresponding to a balance and which would be sustainable would unfortunately not meet the significant water needs for drinking water supply and socio-economic activities.

A PhD thesis [359] was also defended on modelling the groundwater resource on the Horst of Diass. The results shown the Quaternary aquifer is fed by the infiltration of rainwater, particularly in the Mbour area (1); this aquifer is drained by the deep Paleocene and Maastrichtian aquifers (2); the latter drains the Paleocene (3), the lateral flows are from the Maastrichtian of Diass towards the compartment of South Pout and from the compartment of Thiès towards the compartment of Pout through the faults of Pout and Thiès respectively (4).

East to this area a model was built [367] to assess the exploitable potential of the overlying upper (Quaternary/Continental Terminal and Oligo-Miocene) and intermediate (Eocene/Paleocene) aquifers intended for dilution and/or transfer to areas where the quality of the Maastrichtian aquifer is poor. Specific objectives of the modelling effort were to design and implement a management tool by developing a mathematical model that takes into account the specificities of this region with a view to transferring water to areas where the water quality is poor, and to identify in the study area the favorable areas where the overlying water tables offer the best prospects for a good water supply quality. The model provided the definition of scenarios for groundwater exploitation, and represents the synthesis of all the previous works, and the results obtained to improve drinking water services in the area covering the regions of Diourbel, Kaolack, Fatick and Kaffrine. A simple more localised model was built for the eastern part of the above mentioned domain [361]. The results of this study show that the groundwater balance shows significant potential still exploitable from the reservoir.

A MSc thesis [358] dealt with modelling the Maastrichtian aquifer in the Touba area in order to devise a groundwater exploitation strategy for drinking water supply. It provided scenarios for the sustainable groundwater exploitation.

The Saloum hydrologic system, located on the Mid West of Senegal, is an inverse hypersaline estuary where salinity of water substantially exceeds that of seawater with increasing gradient towards inlands [356]. In this system, salinity is highly dependent on rainfall variations and it is governed by the net loss of freshwater due to excess of evaporation over runoff. In this context, saltwater contamination constitutes a serious problem for the Continental Terminal aquifer which bears considerable groundwater resources for water supply. The water table, contained in the formations of the Continental Terminal, characterized by the presence of sand, clay, sandstone, sandy clay and silt, produces most of the water intended for domestic and agricultural supply in the Saloum zone (central west of Senegal). This environment associated with the deficient rainfall conditions, calls out a need to understand the system both from the qualitative and quantitative point of view.

In [355] a hydrogeological model simulating the groundwater flows in the Continental Terminal aquifer and the responses with regard to different scenarios such as additional groundwater abstraction and climatic changes of the southern sector of the Saloum river deltaic areas is presented. The study entails a multidisciplinary methodology combining hydrodynamics, remote sensing and GIS tools, major element geochemistry and isotopic analyses together with groundwater modelling. The 2D model was calibrated using transient time from 1974 to 2012. The results show that rainwater, river and marine salt water constitute the main inflows of the aquifer. Scenarios (2013 to 2050), taking into account the combined impact of increased pumping (of the order of 45%) and decreased recharge (36% on average) show variable lowering of the groundwater table. This model is suggested as a decision support tool for better and sustainable management and guidance for the future groundwater extraction.

In the southern part of the SMB, two recent (2017) technical reports are dealing with modelling in the Casamance watershed. A simple one-layer groundwater flow model [365] was built in order to evaluate the water resources potential of the Oussouye plateau, within the larger framework of mastering and understanding groundwater and surface water availability to meet the multiple needs of the populations of Oussouye. In this area, the groundwater resources are very vulnerable due to the Casamance River and backwaters (*bolongs*, salty channels). Hence, the study aimed at improving the drinking water supply and possibly ensuring the water needs for irrigation and livestock. Modeling results evaluated the renewable resources by rain recharge at 16,296 m3/day, which was less than 1/3 of the withdrawals (4600 m^3 / day) at the time of the study. The Authors also suggested to set-up a monitoring network to monitor the evolution of the piezometric levels and of the groundwater quality over time is necessary (especially at the edge with the bolongs and the Casamance river).

A second local simple one-layer groundwater flow model [366] aimed at evaluating the potential of the Continental Terminal aquifer with a view to supply the touristic Cap Skiring area. The results of this model showed that this aquifer can be exploited rationally, while controlling potential seawater intrusion, and helped defining the areas more prone to groundwater abstraction (also for the populations of Cap Erucken).

1.2 Groundwater modelling efforts in Mauritania.

Few studies have been completed on the groundwater hydrology of Mauritania (Friedel and Finn 2012) and in Earthwise contributors (2020) a detailed review on Mauritanian hydrogeology is presented. However, our research did not retrieve any modelling study performed in Mauritania.

References to the use of GIS desktop software (ArcGIS, MapInfo) are made in RAF/7/011 (2017) and also to the use of PHREEQC. For the latter, we may then suppose that at least a 2D model was developed. However, it was not possible to find any document related to that.

Recently, in the appraisal document for a proposed grant (World Bank 2020) it is mentioned that modelling and study of the Dhar aquifer and the Grès d'Aioun aquifer, two crucial water sources that can enhance Mauritania's resilience to climate change, will be undertaken. This document also mentions support for technical activities such as the improvement of the piezometric network for the monitoring of groundwater resources, training and capacity building for CNRE staff, and strengthening water quality monitoring.

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C2. Groundwater Modelling in Western Africa

The Taoudéni and Iullemeden aquifer systems

West Africa is endowed with water resources shared between several States, both at the level of hydrological basins (Niger, Senegal, etc.) and of transboundary aquifer systems such as those of Iullemeden (IAS), Taoudéni (TAS) and the Senegalo-Mauritanian Basin (SMB). The resources of these transboundary aquifer systems are often poorly known and gradually threatened by the increase in the demand for water, climate change, and quality degradation due to pollution sources. Moreover, the management of these shared water resources is often not concerted.

The Iullemeden and Taoudéni aquifer system is the second largest aquifer on the African continent, of the same order of extent as the Nubian Sandstone Aquifer System (2.6 million km^2) shared by Egypt, the Libya, Sudan and Chad [370]. The two systems are traditionally considered separately, but in geologic continuity through the Gao ditch (Figure C4 [370]).

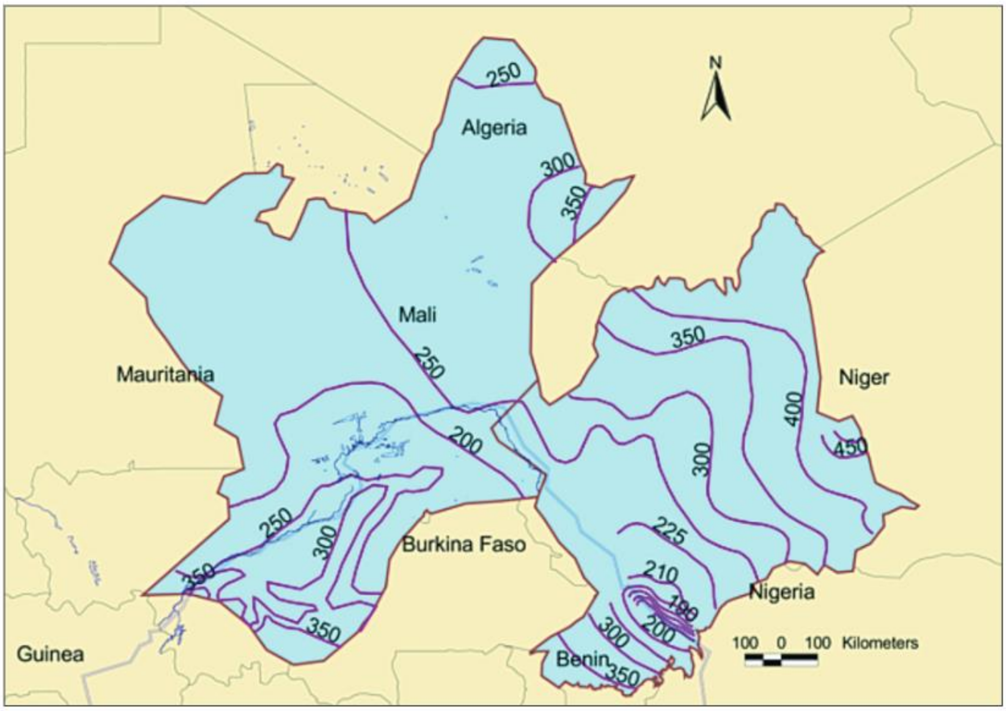

Figure C4. Groundwater head map of the TAS and IAS (from [370]).

C2.1 Groundwater Modelling in the Taoudéni Aquifer System

The Taoudeni Sedimentary Basin is shared among Mali and Mauritania, Algeria and Burkina Faso. It has been studied in the transboundary research "*Gestion intégrée et concertée des ressources en eau des systèmes aquifères d'Iullemeden, Taoudéni Tanezrouft et du fleuve Niger «GICRESAIT*" (*Concerted and Integrated Management of Water Resources in the Iullemeden Aquifer System, Taoudéni / Tanezrouft and the Niger River, GICRESAIT*) [370].

The Taoudéni aquifer system (TAS) represents a very large area, with several basins of complex geometric structure, resulting in high variability in the thickness and nature of the sediment cover, and it is often partly divided by its southern part (the South East Taoudéni).

The Continental Intercalaire (CI) and Continental Terminal (CT) are the main aquifers of the TAS. The continental sedimentary deposits of the Continental Intercalaire in the Taoudeni Basin can be separated into four main regions (Earthwise contributors, 2020):

- in the Khenachich Region the deposits primarily comprise coarse sandstones and conglomerates interbedded with thick clays. Aquifers are shallow and isolated;
- along the south eastern flank of Adrar des Iforas, coarse sandstones are interbedded with shales, forming continuous, multi-layered aquifers. The Tegama sandstone forms the most significant aquifer in this region;
- in the Azaouad region the deposits comprise locally coarse sands interbedded with sandy clays forming a multi-layered aquifer;
- in the Nara ditch region an upper aquifer, comprising mainly sands, is separated from a lower conglomeratic sandstone aquifer by a clay layer. The upper aquifer is unconfined and exploited by many traditional wells.

Borehole yields and transmissivity vary across the four regions described above and average yields are between 9 and 12 m^3/hour with maximum yields up to 50 m^3/hour (in the Nara ditch region; Earthwise contributors, 2020). Transmissivity varies between 10 and 3500 m^2/day, with an average of around 600 m^2/day. The average thickness of the continental aquifers is 150-200 m.

The Continental Terminal formation and the overlying Quaternary deposits are in hydraulic continuity, and are generally considered a single, multi-layered aquifer (Earthwise contributors, 2020). Borehole yields generally range from 8 to 23 m^3/hour, but can exceed 100 m^3/hour in the most productive layers. The unconsolidated aquifers are unconfined and can range in thickness from less than 100 m in the western part of the inland delta to 1000 m in the axial zone of the Gao ditch.

The deep formations of the Infracambrian are in frequent hydraulic continuity with the overlying CI and CT terrains, with groundwater of acceptable quality [370].

The aquifers of the Continental Intercalaire and the Continental Terminal are not clearly separated and are often found in continuity with underlying geological formations, of varied nature, with intergranular or fissured/fractured porosity on a large scale. The overall structure of the basin is disturbed by tectonics, responsible for partitions and very strong variations in thickness and facies of the CI and CT formations. In the sub-basins, the hydrogeological conditions may be very different. There is not a single outlet, but several not yet been fully defined: the Niger River via the Gao ditch, outflow towards the Volta basin and the Gondo plain, on the south-eastern limit of the Taoudéni basin in Burkina Faso [370].

At the scale of the TAS, in [370] this pragmatic criterion of water resource continuity, and the fact that in the northern part of the TAS, there is low density of hydrogeological information and most of the boreholes are only in a situation of partial penetration aquifers, lead to model the TAS as a single layer.

The spatial distribution and the list of modelling efforts retrieved for the TAS are presented in Figure C5 and Table C2 respectively. For the detailed information on the models the reader is referred to Annex 1. Results of the regional model [370] show for TAS considerable resources (11 billion m^3), of good quality and not very sensitive to climatic variations. Regions with exceptional potential have been identified. Scenarios for the exploitation of the Taoudéni aquifer systems with a continuous increase in water needs have been simulated until 2050. The impact of the increased water requirements remains low in the case of a classic scenario. The calculated drawdowns do not exceed 3.5 meters. The most sensitive sectors are located near areas that already exploit groundwater: agglomeration of Sikasso, Douentza, Goundam in Mali, Bordj Badji Mokhtar sector in Algeria and Fossé de Nara (Mali)/Dhar de Néma (Mauritania).

It should be noted that for both the TAS and the IAS, a single year of surplus makes it possible to make up for the drop in levels linked to several years of deficit in areas where there is a significant recharge [370].

Aside from the model simulating the whole TAS [370], few other modelling efforts (of local to sub-regional extension) were implemented, mostly in the South Eastern part. All the models implemented in this system were implemented by means of the MODFLOW code and cover part of the Mali country. No models were retrieved in Mauritania and Algeria.

A local model of the Klela Basin [152], southern Mali at the border with Burkina Faso, where the groundwater is the only permanent water resource (used for drinking water and irrigation) was built. Due to climate change, this vital resource is being threatened. The aim of the modelling effort was to evaluate the impact of climate change on groundwater resources using the RCP4.5 (Representative Concentration Scenario 4.5 W/m^2) climate scenario. The results of the simulated MODFLOW model showed a decrease in groundwater levels over time. The Bani model [110] showed rainfall recharge and evapotranspiration to influence simulated groundwater levels and groundwater volume available, while increased pumping rates, due to population growth, showed little effect. The change in groundwater levels resulting from climatic parameters may have negative implications, especially during several consecutive years of decreased precipitation, such as drought, or in case of downward trends anticipated for precipitation. Of very local interest is the model developed for the area of the Horongo village (in the near of Bamako, [27-28]). This was developed within the framework of a MSc master thesis with very limited objectives.

The simple 2D cross-sectional Gondo plain model [371], between Mali and Burkina Faso with an area of about 30 000 km^2, was built to improve understanding of groundwater recharge and hydrodynamics. Even the model described in [369] was built to better understand the aquifer system for future groundwater resource management and to compare methods for evaluating rainfall recharge. The modelling of groundwater flow in steady and in transient state allowed inferring the hydrodynamic parameters.

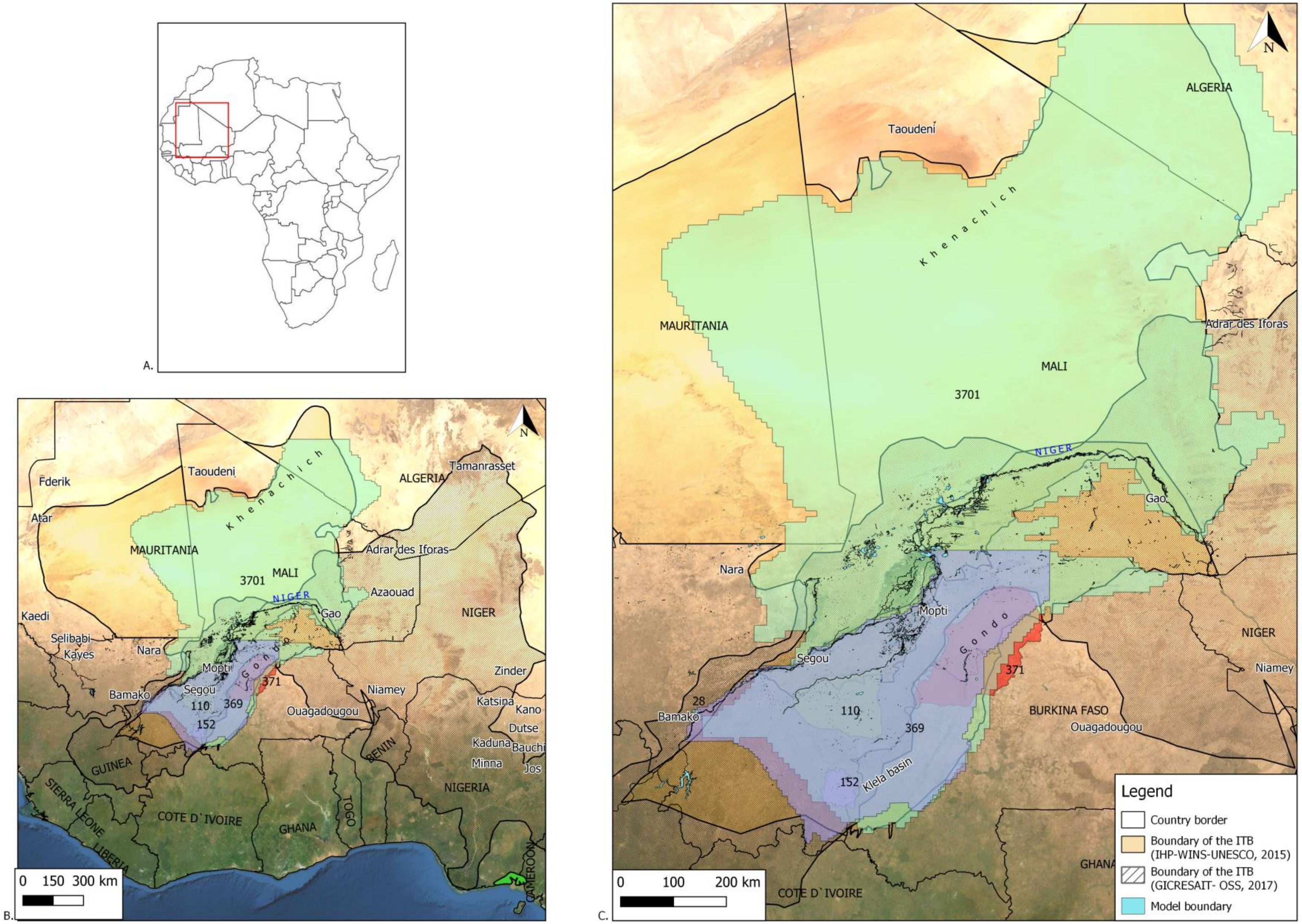

Figure C5. Boundary of the Taoudéni Aquifer System, location and extension of the retrieved modelled areas.

ID	Year	Document Type	Objective short	Country	Model name	Main aquifer investigated	Watershed	Code(s) used for simulation
27	2009	MSc Thesis	Groundwater management	Mali	Horongo	Residual soils on sandstones	Niger	MODFLOW-2000
28	2013	Research paper	Groundwater management	Mali	Horongo	Residual soils on sandstones	Niger	MODFLOW-2000
110	2009	Research paper	Climate change impact	Mali	Bani model	Koutiala and Bandiagara Sandstones (fissured/fractured)	Bani (tributary of the Niger river)	MODFLOW-2000
152	2016	Research paper	Climate change impact	Mali	Klela basin	Sandstone aquifer	Lotio River (Bani river)	MODFLOW
369	2011	PhD Thesis	Understanding hydrology	Mali-Burkina Faso	South east border of the sedimentaryu basin of Taoudeni	Alluvial-type sedimentary formations	Niger	MODFLOW
370	2017	Technical report	Understanding hydrology	Algeria, Benin, Burkina Faso, Mali, Mauritania, Niger, Nigeria	Taoudèni/Tanezrouft aquifer system (SAT)	Continental Terminal/Continental Intercalaire	Niger	MODFLOW
371	2010	PhD Thesis	Understanding hydrology	Mali-Burkina Faso	Gondo plain	Continental terminal/ Infracambrian	Sourou	MODFLOW

Table C2. Table summary of the models retrieved for the Taoudéni aquifer system.

C2.2 Groundwater Modelling in the Iullemeden Aquifer System

Two main transboundary aquifers (the Continental Intercalaire and the Continental Terminal) constitute the Iullemeden Aquifer System (IAS), shared in its major part by Mali, Niger and Nigeria over 500,000 km2.

The IAS has a geometric structure in a unique basin (Figure C6), and the sedimentary series it contains is relatively simple [370]:

a) structure in large and deep basin, relatively simple in shape, closed to the north by reliefs (Aïr, Hoggar and Adrar des Iforas) and open to the south in the structural collapse zone of the Parc du W, where the Niger river drains the CI and CT aquifers to a single major outlet represented by the valley of the Niger river at its entry into Nigeria, in the area of convergence of the borders of Benin and Burkina (West branch of the West African Rift Subsystem).

b) the CI and CT aquifers are separated by an intermediate clay sequence (Irhazer clays, papery schists, etc.).

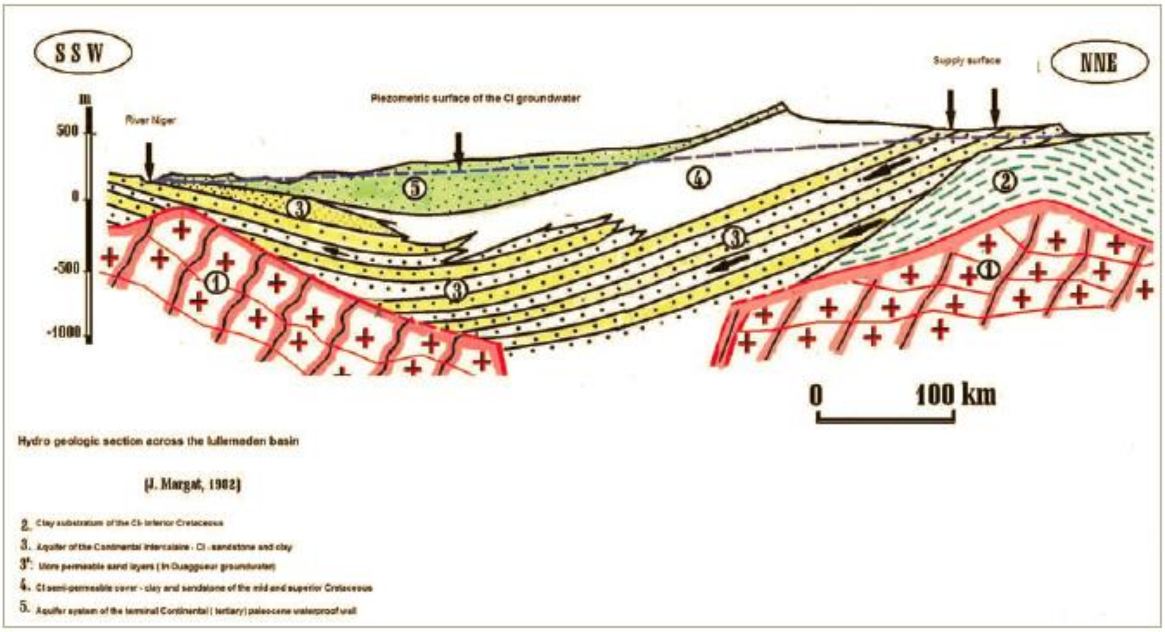

Figure C6. Cross-section across the Iullemeden Aquifer System (from Margat 1982).

The spatial distribution and the list of modelling efforts retrieved for the TAS are presented in Figure C7 and Table C3 respectively. For the detailed information on the models the reader is referred to Annex 1.

The spatial distribution and the list of modelling efforts retrieved for the TAS are presented in Figure 3 and Table 2 respectively. For the detailed information on the models the reader is referred to Annex 1. The groundwater flow simulation model for the aquifers of the Continental Intercalaire and the Continental Terminal of the Iullemeden aquifer system carried out in 2006 [372] took into account two distinct layers, each corresponding to one of these two large groups. This study has led to the first modeling of the Iullemeden aquifer system for an evaluation of the exploitable resources through the analysis of the available information.

In [370] a regional groundwater flow model coupled to the one of the TAS was implemented. The IAS presents considerable resources (8 billion m3) of good quality and not very sensitive to climatic variations. Scenarios for the exploitation of the Iullemeden aquifer system with a continuous increase in water needs have been simulated until 2050. The results show that the most important drawdowns are located at the Nigeri-Nigerian border. In a pessimistic scenario, drawdowns are less than 4 meters over most of the aquifer system. In sectors close to the limits of the aquifer, the effects would be more impacted (Nara Ditch, Gondo) with simulated drawdowns of around ten meters. It should be noted that for both the SAT and the SAI, a single year of surplus makes it possible to make up for the drop in levels linked to several years of deficit in areas where there is a significant recharge. The entire region covered by the project suffers from a serious lack of good knowledge of underground flows. At the end of the project, the acquisition of additional data for the establishment of the piezometric reference maps was suggested along with a review of national databases. The regional model developed has made it possible to identify areas which deserve to be better studied and which should be the subject of local models. The regional model will serve, among other things, as boundary conditions for local models that will be developed later when conditions allow. The production of local digital models can only be optimized by improving knowledge of local aquifer systems. It is relevant to notice that, in the frame of a recognised need for digitalisation, among the recommendations was the need for capacity building with infrastructural (installation of dedicated Internet broadcast servers), software (renewal of GIS licenses and purchase or request for development of solutions for the deployment of Web Mapping) and training for GIS, databases & modelling.

In [2] an equivalent porous medium approach was used to characterize groundwater surface water interaction in geologically complex fractured and sedimentary aquifers, with a high resolution fully integrated surface-subsurface hydrological model in semiarid urban watershed of Niamey, Niger. Simulation results show that exchange flux between groundwater and surface water are important processes in the basin, with the Niger River acting primarily as a gaining stream, with local losing zones. The basin average water balance highlights the importance of plant transpiration (58% of total rainfall) over surface evaporation (8%), with groundwater recharge of up to 5% of total rainfall. Overland flowand infiltration account for 11% and 16% of the total annual rainfall respectively, and groundwater discharge to the river is 2% of the total rainfall.

A model-based investigation of surface runoff and groundwater recharge at mesoscale (∼5000 km^2) is discussed in [46] A meso-scale surface model (MSSM), which simulates inflows to endorheic ponds and depressions, was developed based on an existing fine-scale catchment model (FSCM), to allow for the coupled surface water–groundwater modelling in this semi-arid area. This surface model upscaling was quite successful in retaining at the larger scale the original fine-scale modelling capabilities, adding only very reasonable predictive uncertainty, while gaining the ease and simplicity in implementation needed for the coupled, meso-scale modelling. The coupled model, based on the indirect recharge paradigm, was able to reproduce the over-all observed inter-annual dynamics of the water table and its spatial structure satisfactorily, with hydrodynamic parameter values within the range of initial field estimates. The coupled simulations do substantiate the possible explanation of the ubiquitous water table rise by increased concentrated recharge at specific points in the landscape. For the first time, a method for assessing meso-scale surface runoff in the endorheic Sahel is proposed, integrated with ground-water hydrodynamics, and tested against the regional water table dynamics, providing encouraging results at this significant spatial scale.

Finally, It is worth noting that one of the outcomes of the project “Managing Hydrogeological Risk in the Iullemeden Aquifer System” (GEF IDS: 2041 UNEP Terminal Evaluation (2009) https://iwlearn.net/iw-projects/2041/results) is related to the fact that “*at national level, academics in Mali are developing university courses in groundwater modelling to build future capacity and capability, and looking to use the tools for national issues*”.

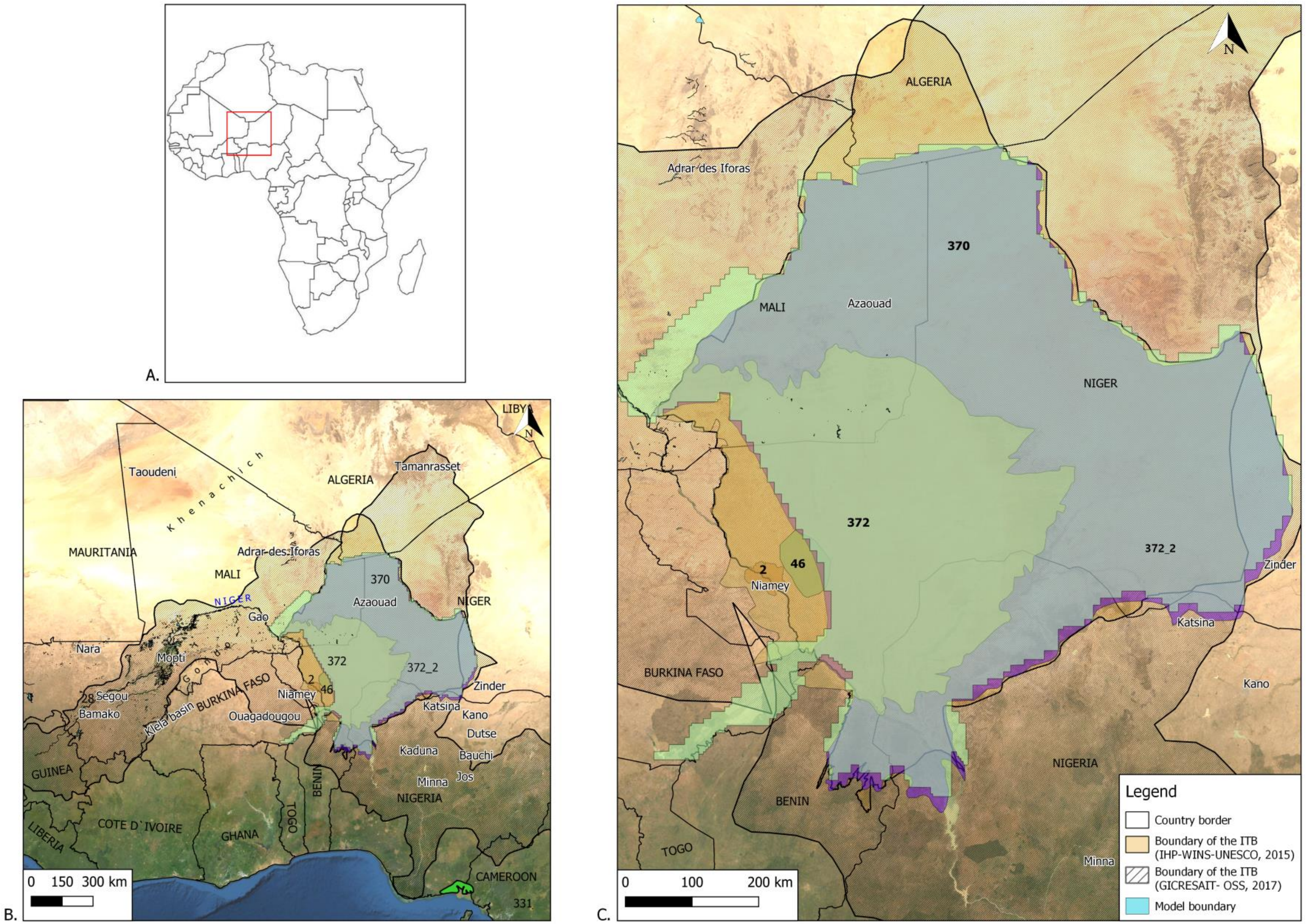

Figure C7. Boundary of the Iullemeden Aquifer System, location and extension of the retrieved modelled areas.

ID	Year	Document Type	Objective_short	Country	Model name_1	Main aquifer investigated	Watershed	Code(s) used for simulation
2	2020	Research paper	Understanding hydrology	Niger	Niamey urban watershed	Sandstone CT3 aquifer, fractured Precambrian basement aquifers	Niger	HydroGeoSphere
46	2011	Research paper	Understanding hydrology	Niger	Dallol Bosso valley	Continental Terminal	Niger	MODFLOW
370	2017	Technical report	Understanding hydrology	Niger, Algeria, Benin, Burkina Faso, Mali, Mauritania, Nigeria	Taoudèni/Tanezrouft aquifer system (SAT)	Continental Terminal/Continental intercalcaire	Niger	MODFLOW
372	2011	Technical report	Understanding hydrology	Niger, Mali, Nigeria	Iullemeden aquifer system	Continental terminal/ Continental intercalary	Niger River	MODFLOW

Table C3. Table summary of the models retrieved for the Iullemeden aquifer system.

References (not related to modelling studies)

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