Answers to referee #1

General Comments

The paper by O. Conrad et al. presents general structure and capabilities of the opensource GIS, SAGA. This software has become an important contribution to a health and ever growing free and open-source software ecosystem for geographic information analysis. A paper summarizing SAGA's structure and features has therefore been overdue and is likely to be cited very often.

Specific Comments

R: "While the paper's description of software history, structure and philosophy and the general overview of its capabilities is very welcome, I feel that the review of SAGA applications in section 3 could be substantially shortened. To showcase the diversity of applications in which SAGA has been used, perhaps one or two (page-filling) tables and a brief textual summary would prove more useful."

Answer: we followed your suggestion and added a table that gives an overview to the references categorized by the addressed research fields; this coincides also with the suggestion of referee #2 to provide a '*visualization of the fields*', which currently make use of SAGA. We also agree that section 3 looks a bit lengthy, especially when compared to the following sections. However, we refrain from shortening its content substantially. The software SAGA evolved within scientific projects and as also highlighted by referee #2 the development was largely driven by science. Therefore, we think the science behind is an important aspect of SAGA and the various studies better reflect the wide scope and applicability than just a presentation of the functionality.

Other aspects, however, that would add to the relevance of this paper, are currently missing. In particular, a general comparison of SAGA's capabilities and features to other commercial as well as open-source GIS would give the reader a better idea as to what to expect from this software, and it would help to situate SAGA within the opensource GIS ecosystem. This could again partly be presented in tabular form, and/or it could involve references in the text to comparable (or not so comparable) features in well-known software, e.g. SAGA tool chains seem to be similar to ArcGIS ModelBuilder, and Python geoprocessing in ArcGIS is comparable to Python or R scripting with SAGA (is it?). These comparisons would (likely) reveal sets of GIS functions that are currently not available in SAGA tools (e.g. address geocoding or vehicle routing?), inspiring the reader to consider contributing to SAGA development.

For comparision with other open source GIS references are now given in the introduction.

During the last ten to fifteen years Free and Open Source Software (FOSS) became a recognized counterpart to commercial solutions in the field of geographic information systems and science. Steiniger and Bocher (2009) give an overview to free and open source Geographic Information System (GIS) software with a focus on desktop solutions. More recently, Bivand (2014) discusses FOSS for geocomputation. The System for Automated Geoscientific Analyses (SAGA) (http://saga-gis.org), subject of this paper, is one of the recognized developments in this field.

Reference to ArcGIS/QGIS model builder was added:

Tool chains are comparable to the models created with ArcGIS ModelBuilder (ESRI, 2015) or QGIS Processing Modeler (QGIS Development Team, 2014), but unlike these, SAGA does not yet include a graphical tool chain designer.

we added some text to the scripting chapter to to outline interrelations between SAGA and the '*GIS ecosystem*'. Scripting and integration with other systems

The SAGA command line interpreter (CLI) is used to execute SAGA tools from a command line environment without any visualization or data management facilities. Therefore, the file paths for all input and output data have to be specified within the command. The CLI enables the creation of batch or shell script files with subsequent calls of SAGA tools to automate complex work flows and automatically apply them to similar data sets. Furthermore, the CLI allows calling SAGA tools from external programs in an easy way. This feature is used by the RSAGA package, which integrates SAGA tools with the R scripting environment (Brenning, 2008). Likewise, the Sistema EXTremeño de ANálisis TErritorial (SEXTANTE) makes SAGA tools accessible for various Java based GIS programs (gvSIG, OpenJUMP). In 2013 SEXTANTE was ported to Python to become a functional addition to QGIS (QGIS Development Team, 2014), another popular free and open source GIS software, thus spreading SAGA tools amongst many more GIS users. Alternatively to CLI based scripting, the SAGA API can also be accessed directly from Python. This connection is generated by means of the Simplified Wrapper and Interface Generator SWIG (http://www.swig.org) and provides access to almost the complete API. While this allows higher level scripting, the CLI remains easier to use for most purposes.

Another option of integrating SAGA is direct linkage of the API. A very recent development is the integration of SAGA by the ZOO-Project (http://zoo-project.org/), which is a framework for setting up Web Processing Services (Fenoy et al., 2013). MicroCity (http://microcity.sourceforge.net) is a branch of SAGA, which adds support for the script programming language LUA, and has been used for city road network analyses (Sun, 2015). Laserdata LiS is proprietary software, mainly a toolset extension for the work with massive point data from LiDAR prospection (http://www.laserdata.at).

Table 1 summarizes the third party software mentioned above and underlines that SAGA is recognized first of all as geoprocessing engine. Only MicroCity and LiS make at least partly use of SAGA's GUI capabilities.

[Table 1: Software utilizing SAGA.]

Software	Interface	Remarks
QGIS	CLI	Processing Modeler
gvSIG	CLI	SEXTANTE
OpenJUMP	CLI	SEXTANTE
R	CLI	RSAGA
ZOO	API	Web Processing Service

Overall, I believe that this publication will be a valuable contribution to documenting the current state of free and open-source geographic information analysis, but I recommend major modifications based on the above comments.

Additional detailed comments and editorial changes:

P2272L8 "modular organized" - omit "organized"

done

P2272L10 "easily approachable" - change to "user-friendly"

done

P2272L11 "scripting and low level programming languages like R and Python" - neither of these is "low level", and instead of "scripting language", "interpreted language" would be more accurate; omit "scripting and low level"

done

P2272L21 Provide some context on free and open-source software for the geosciences / geography / geographic data analysis before focusing on SAGA.

we added the following paragraph to give a context

During the last ten to fifteen years Free and Open Source Software (FOSS) became a recognized counterpart to commercial solutions in the field of geographic information systems and science. Steiniger and Bocher (2009) give an overview to free and open source Geographic Information System (GIS) software with a focus on desktop solutions. More recently, Bivand (2014) discusses FOSS for geocomputation. The System for Automated Geoscientific Analyses (SAGA) (http://saga-gis.org), subject of this paper, is one of the recognized developments in this field.

P2272L5 change "in behalf" to "on behalf"

done

Much of the current Introduction should better be placed in a separate section giving a brief history of SAGA; I noticed some overlap with the current section 2

We feel that a brief history should be part of the introduction.

First paragraph of the current introduction is too long. In general throughout the manuscript, paragraphs tend to be rather long - consider splitting them into shorter paragraphs

done

P2273L21 "SAGA got a growing global user community" - rephrase: "SAGA's global user community has been growing"

according to referee #2, we will replace *'got'* with *'built-up'*

P2273L28 "raised" - change to "rose"

done

P2274L7 "by a review of" - change to "by reviewing"

done

P2274 SAGA as FOSS - Free software and open-source software are overlapping concepts with different philosophical motivations. My feeling is that SAGA is "free" rather than (just) "open-source". Use proper academic reference when introducing the concepts of free and open-source software.

yes, we agree; academic reference will be added

P2274L24 "base" - change to "basis"

done

P2275L2 "discussion" - change to "comments"

done

P2275L4 "widespread and effective" seems redundant

we will remove *'and effective'*

P2276 and elsewhere: change "meta data" to "metadata", "data base" to "database"

done

P2277L24 Is there any academic reference that could be used when referring to GDAL?

yes, we refered to Bivand (2014) GeoComputation and Open-Source Software (In: Abrahart & See, GeoComputation)

Within this group a toolset interfacing the Geospatial Data Abstraction Library (GDAL) should be highlighted (http://www.gdal.org) (Bivand, 2014).

P2279L11 "Summarizing" - change to "In summary,"

done

P2279 Section 2.4 Perhaps a small table would be suitable for summarizing which software uses SAGA modules or API and how

done

Section 3 - Much of this could be summarized in one or two (large, page-filling) table in order to make the text more readable and the breadth of applications more accessible to the reader. E.g. the long paragraph that makes up most of section 3.1.4 is very difficult to digest by the reader, and most other subsections of section 3 follow a similar style of briefly mentioning numerous studies that used SAGA

done, also see our above answer in the *specific comments* section

Answers to referee #2

General Comments

This paper nicely outlines the progression of SAGA from a specialized digital terrain analysis software to a full GIS platform which seems to rival the capabilities of other GIS software. By having the development be guided by current research, SAGA has become very broad in scope and, as described in the paper, is being used and developed in a wide range of fields. Much of the success of the software seems to be due to the creation of an API which has enabled developers to add their own methods. Having an interface to R and Python has no doubt increased the power of the software. While the paper briefly describes some of the features and architecture of SAGA, I found these descriptions to be sparse, i.e., this is a non-technical review. Rather, the main focus of this paper is to highlight the research being done using SAGA and thus demonstrates its usability over a wide variety of subject areas. The paper also makes it clear that it is this research that is driving SAGA's development. This paper is of high quality and upon some minor revisions will make a very useful contribution to the literature and help introduce potential users to the software.

Specific Comments

Introduction *Is it possible to provide a breakdown of the various files/research areas these 700 modules occur in? I'm thinking a pie diagram or something that would show which fields are really driving the development.*

Yes, we added a pie chart showing the number of tools falling into categories like terrain analysis, spatial and geostatistics, or image analysis and some subcategories (e.g. terrain analysis related to hydrology or topoclimate).

Figure 4 gives a rough overview to the different fields of data analysis and management addressed by the SAGA toolset. The categories have been derived from the menu structure, which might not reflect accurately the usability of all tools, e.g. in the case of multipurpose tools. But it can be seen that there is a quite comprehensive set of general tools for raster as well as vector data analysis and management and also that terrain analysis still can be seen as a strength of SAGA..

Further on in the paper a wide variety of references are given and it would be nice to have a visualization of the fields which are currently using the software.

Following a suggestion of referee #1 we added a table that gives an overview of the references categorized by the addressed research fields.

The System *A good overview of the various components of the software is provided and gives the reader an idea of these components fit together and how development of modules works. How do these features compare with other software available, such as QGIS? I do not have a ton of experience using GIS open-source software but am eager to know what sets SAGA apart from the others.*

Similar has been suggested by referee #1 too; For comparision with other open source GIS references are now given in the introduction.

During the last ten to fifteen years Free and Open Source Software (FOSS) became a recognized counterpart to commercial solutions in the field of geographic information systems and science. Steiniger and Bocher (2009) give an overview to free and open source Geographic Information System (GIS) software with a focus on desktop solutions. More recently, Bivand (2014) discusses FOSS for geocomputation. The System for Automated Geoscientific Analyses (SAGA) (http://saga-gis.org), subject of this paper, is one of the recognized developments in this field.

we added some text to the scripting chapter to outline interrelations between SAGA and the *'GIS ecosystem'*. Scripting and integration with other systems

Scripting and integration with other systems

The SAGA command line interpreter (CLI) is used to execute SAGA tools from a command line environment without any visualization or data management facilities. Therefore, the file paths for all input and output data have to be specified within the command. The CLI enables the creation of batch or shell script files with subsequent calls of SAGA tools to automate complex work flows and automatically apply them to similar data sets. Furthermore, the CLI allows calling SAGA tools from external programs in an easy way. This feature is used by the RSAGA package, which integrates SAGA tools with the R scripting environment (Brenning, 2008). Likewise, the Sistema EXTremeño de ANálisis TErritorial (SEXTANTE) makes SAGA tools accessible for various Java based GIS programs (gvSIG, OpenJUMP). In 2013 SEXTANTE was ported to Python to become a functional addition to QGIS (QGIS Development Team, 2014), another popular free and open source GIS software, thus spreading SAGA tools amongst many more GIS users. Alternatively to CLI based scripting, the SAGA API can also be accessed directly from Python. This connection is generated by means of the Simplified Wrapper and Interface Generator SWIG (http://www.swig.org) and provides access to almost the complete API. While this allows higher level scripting, the CLI remains easier to use for most purposes.

Another option of integrating SAGA is direct linkage of the API. A very recent development is the integration of SAGA by the ZOO-Project (http://zoo-project.org/), which is a framework for setting up Web Processing Services (Fenoy et al., 2013). MicroCity (http://microcity.sourceforge.net) is a branch of SAGA, which adds support for the script programming language LUA, and has been used for city road network analyses (Sun, 2015). Laserdata LiS is proprietary software, mainly a toolset extension for the work with massive point data from LiDAR prospection (http://www.laserdata.at).

Table 1 summarizes the third party software mentioned above and underlines that SAGA is recognized first of all as geoprocessing engine. Only MicroCity and LiS make at least partly use of SAGA's GUI capabilities.

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OpenJUMP	CLI	SEXTANTE
R	CLI	RSAGA
ZOO	API	Web Processing Service

Review of SAGA related studies and applications *Again, I think a visualization of the 'broad spectrum of geoscientific analysis and modeling applications . . .' would be insightful.*

see above

Minor Details

P2273 L2-3. Remove comma following 'both' and 'up' following 'data,'.

done

L9. Remove 'e.g.'.

done

L14. Change 'skills' to 'features'.

done

L.21. Change 'got' to 'attained' or 'built up'.

done

P2274 L.21. Replace 'has been' with 'was'. This occurred at a single point in the past, so it is over and you should use 'was'. There are a few points in this article where this change needs to occur.

done

P2277 L10-11. Not sure I understand the meaning of this sentence.

Changed to:

Furthermore, this possibility of executing any loaded tool is used for the processing of tool chains. Tool chains are comparable to the models created with ArcGIS ModelBuilder (ESRI, 2015) or QGIS Processing Modeler (QGIS Development Team, 2014), but unlike these, SAGA does not yet include a graphical tool chain designer. Tool chains are defined in a simple XML based code that is interpreted by the tool chain class, another variant of the general tool class.

P2280 L16. Change to 'has remained' a major focus?

done

P2281 L8. Remove 'for instance'.

done

P2284 L1. 'The integration of new tools,. . ."

done

P2292 L18. Please fully spell out 'bio- resp.' I'm not sure what this is.

(resp. = respectively), changed to *'...biogeography and particularly vegetation geography.'*

biogeography and particularly plant geography

P2294 L11-13. Unclear. This sentence needs rephrasing around the '. . . but likewise the outcome,. . .' part.

we wanted to point out that open source codes are the ideal complement for a scientific publication, because it gives full insight to a method's implementation

SAGA is not only a research supporting tool but likewise its outcome, which complements related scientific publications with the ultimate documentation of used methodologies in the form of source codes

System for Automated Geoscientific Analyses (SAGA) v. 2.1.4

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[*] Correspondence to: B. Bechtel (benjamin.bechtel@uni-hamburg.de)

Abstract: The System for Automated Geoscientific Analyses (SAGA) is an open-source Geographic Information System (GIS), mainly licensed under the GNU General Public License. Since its first release in 2004, SAGA has rapidly developed from a specialized tool for digital terrain analysis to a comprehensive and globally established GIS platform for scientific analysis and modeling. SAGA is coded in C++ in an object oriented design and runs under several operating systems including Windows and Linux. Key functional features of the modular software architecture comprise an application programming interface for the development and implementation of new geoscientific methods, an user friendly graphical user interface with many visualization options, a command line interpreter, and interfaces to interpreted languages like R and Python. The current version 2.1.4 offers more than 600 tools, which are implemented in dynamically loadable libraries or shared objects and represent the broad scopes of SAGA in numerous fields of geoscientific endeavor and beyond. In this paper, we inform about the system's architecture, functionality, and its current state of development and implementation. Further, we highlight the wide spectrum of scientific applications of SAGA in a review of published studies with special emphasis on the core application areas digital terrain analysis, geomorphology, soil science, climatology and meteorology, as well as remote sensing.

Gelöscht: organized

Gelöscht: easily approachable

Gelöscht: scripting and low level programming

Gelöscht: 700

1 Introduction

During the last ten to fifteen years Free and Open Source Software (FOSS) became a recognized counterpart to commercial solutions in the field of geographic information systems and science. Steiniger and Bocher (2009) give an overview to free and open source Geographic Information System (GIS) software with a focus on desktop solutions. More recently, Bivand (2014) discusses FOSS for geocomputation. The System for Automated Geoscientific Analyses (SAGA) (http://saga-gis.org), subject of this paper, is one of the recognized developments in this field.

SAGA has been designed for an easy and effective implementation of spatial algorithms and hence serves as a framework for the development and implementation of geoscientific methods and models (Conrad, 2007). Today, this modular organized programmable GIS software offers more than 600 methods comprising the entire spectrum of contemporary GIS from multiple file operations, referencing and projection routines over a range of topological and geometric analysis of both raster and vector data up to comprehensive modeling applications for various geoscientific fields.

Gelöscht: The System for Automated Geoscientific Analyses (SAGA) (http://saga-gis.org)

Gelöscht: Geographic Information System (GIS)

Gelöscht: 700

Gelöscht: ,

Gelöscht: ,

Gelöscht:

The idea for the development of SAGA evolved in the late 1990s during the work on several research and development projects at the Dept. for Physical Geography, Göttingen, carried out on behalf of federal and state environmental authorities. In view of the specific needs for high quality and spatially explicit environmental information of the cooperating agencies, the original research focus was the analysis of raster data, particularly of Digital Elevation Models (DEM), which have been used to predict soil properties, terrain controlled process dynamics as well as climate parameters at high spatial resolution. The development and implementation of apparently new methods for spatial analysis and modeling resulted in the design of three applications for digital terrain analysis, namely SARA (System zur Automatischen Reliefanalyse), SADO (System für Automatische Diskretisierung von Oberflächen) and DiGeM (Programm für Digitale Gelände-Modellierung), each with specific features but distinctly different architectures.

Gelöscht: in

Gelöscht: e.g.

Gelöscht: skills

Gelöscht: .

Due to the heterogeneity of the applied operating systems and tools in the working group a cross operating system platform with integrated support for geodata analysis seemed necessary for further development and implementation of geoscientific methods. Due to the lack of a satisfying development platform at that time, SAGA has been created as a common developer basis and was first published as Free Open Source Software in 2004 in order to share its advantageous capabilities with geoscientists worldwide. Since then SAGA built up a growing global user community (Figure 1), which also led to many contributions from outside the developer core team and moreover fostered the foundation of the SAGA User Group Association in 2005, aiming to support a sustainable long-term development covering the whole range of user interests. Since 2007 the core development group of SAGA is situated at the University of Hamburg, coordinating and actively driving the development process.

[Figure 1. Total downloads by Country (2004-2014, source: SourceForge.net 2014).]

The momentum and dynamics of the SAGA development in the past 10 years is mirrored in both, the increasing number of methods and tools (Figure 2) which rose from 119 tools in 2005 (version 1.2) up to more than 600 tools in the present version 2.1.4., and, particularly, in the fast growing user community. With about 100.000 downloads annually in the last three years (Figure 3), SAGA today is an internationally renowned GIS developer platform for geodata analysis and geoscientific modeling. Figure 4 gives a rough overview to the different fields of data analysis and management addressed by the SAGA toolset. The categories have been derived from the menu structure, which might not reflect accurately the usability of all tools, e.g. in the case of multipurpose tools. But it can be seen that there is a quite comprehensive set of general tools for raster as well as vector data analysis and management and also that terrain analysis still can be seen as a strength of SAGA..

[Figure 2. Number of tools between 2005 (v1.2) and 2014 (v2.1.4).]

[Figure 3. Average monthly downloads per year (source: SourceForge.net 2014).]

[Figure 4. Number of tools by category. Subcategories are shown for the three largest groups grid tools, shapes tools, and terrain analysis.]

This paper aims to respond to the frequent user requests for a review article. In the first section, we introduce the architecture of the SAGA framework, the state of development and implementation and highlight basic functionalities. Thereafter, we demonstrate its utility in various geoscientific disciplines by reviewing important methods as well as publications in

Gelöscht: got

Gelöscht: raised

Gelöscht: modules

Gelöscht: 700

Gelöscht: modules

Gelöscht: ¶
[Figure 2. Left: Average monthly downloads per year (source: SourceForge.net 2014); Right: number of tools between 2005 (v1.2) and 2014 (v2.1.4).]

Gelöscht: a review of

the core fields of digital terrain analysis and geomorphology, digital soil mapping, climatology and meteorology, remote sensing and image processing.

2 The System

The initial motivation for the SAGA development was to establish a framework that supports an easy and effective implementation of algorithms or methods for spatial data analyses. Furthermore, the integration of such implementations in more complex work flows for certain applications and the immediate accessibility in a user friendly way was one major concern. Thus, instead of creating one monolithic program, we designed a modular system with an Application Programming Interface (API) at its base, method implementations, in the following referred to as tools, organized in separate program or tool libraries and a Graphical User Interface (GUI) as a standard front end (Figure 5). A command line interpreter as well as additional scripting environments were integrated as alternative front ends to run SAGA tools.

Gelöscht: Figure 3

[Figure 5: System architecture]

Gelöscht: Figure 3

In 2004, SAGA was firstly published as free software. Except for the API, source codes are licensed under the terms of the GNU General Public License (GPL) (Free Software Foundation, 2015). The API utilizes the Lesser GPL (LGPL) which also allows developing proprietary tools on its basis. The SAGA project is hosted at SourceForge (http://sourceforge.net), a web host for FOSS projects providing various additional services like version control systems, code trackers, forums and newsgroups. Although many details changed since its first version, the general system architecture remained the same. The following comments refer to the most recent SAGA version 2.1.4.

Gelöscht: has been

Gelöscht: Free and Open Source Software (FOSS)

Gelöscht: (fsf.org)

Gelöscht: base

Gelöscht: ¶

Gelöscht: discussion refers

The system is programmed in the widespread C++ language (Stroustrup, 2014). Besides its support for object oriented programming, one of its advantages is the availability of numerous additional GPL libraries and code snippets. Apart from the C++ standard library SAGA's core system solely depends on the cross platform GUI library wxWidgets (Smart et al., 2005). Especially the GUI extensively accesses the classes and functions of wxWidgets, but also the API employs the library, amongst others for string manipulation, platform independent file access, dynamic library management and XML (eXtensible Markup Language) formatted

Gelöscht: and effective

input and output. Several SAGA tool libraries link to other third party libraries of which some are discussed later more explicitly. Due to the implementation of the wxWidgets library, SAGA compiles and runs on MS Windows and most Unix like operating systems including FreeBSD and with some limitations regarding the GUI MacOSX. Makefiles and projects are provided for gcc and VisualC++ compilers with support for parallel processing based on the OpenMP library (http://openmp.org).

2.1 Application Programming Interface

The main purposes of SAGA's API are the provision of data structures, particularly for geodata handling, and the definition of tool interfaces. Central instances to store and request any data and tools loaded by the system are the Data Manager and the Tool Manager.

Besides these core components, the API offers various additional classes and functions related to geodata management and analysis as well as general computational tasks, comprising tools for memory allocation, string manipulation, file access, formula parsing, index creation, vector algebra and matrix operations, and geometric and statistical analysis. In order to support tool developers, an API-documentation is generated by means of the Doxygen help file generator (http://www.doxygen.org) and published at the SAGA homepage (http://www.saga-gis.org/saga_api_doc/html).

All classes related to geodata share a common base class that provides general information and functionality such as the data set name, the associated file path, and other specific metadata (Figure 6). The supported data types currently comprise raster (grids) and tables with or without a geometry attribute, e.g. vector data representing either point, multipoint, polyline or polygon geometries (shapes). Specific vector data structures are provided by point cloud and TIN classes. The point cloud class is a container for storing mass point data as generated for instance by LiDAR scans. The TIN class creates a Triangular Irregular Network for a given set of points providing topological information concerning point neighborhoods. Each data type supports a generic built-in file format. Raster data use a SAGA specific binary format with an accompanying header. Table data use either tabbed text, comma separated values, or the DBase format. The latter is also applied for storing vector data attributes with the ESRI shapefile format. In order to enhance read and write performance, point clouds also employ a SAGA specific binary file format. Besides, each stored data file is accompanied by a metadata file providing additional information such as map projection and original data

Gelöscht: meta data

Gelöscht: Figure 4

Gelöscht: meta data

source. Additionally, the metadata contain a data set history, which assembles information about all tools and settings that have been involved to create the data set.

Gelöscht: meta data

[Figure 6: Data object hierarchy]

Gelöscht: Figure 4

SAGA tools are implemented in dynamically loadable libraries or shared objects, thus supporting the concept of modular plug-ins. Each SAGA tool is derived from a tool base class, which is specified in the API and defines the standard interface and functionality. In this class, the tool specific input and output data of various data types as well as tool options are declared in a parameter list. At least two functions of the base class have to be implemented by each tool. The constructor defines the tool's interface with its name, a description about its usage and methodology, and the list of tool specific parameters. Its parameter list is automatically evaluated by the system's frame work prior to the execution of a tool. The execution itself is started by a call to the second compulsory function, which implements the tool's functionality.

Specialized variants of the tool base class are available for enhanced processing of single raster systems or for interaction of the tool with the GUI (i.e. to respond to mouse events occurring in a map). The API uses a callback system to support communication with the front end, e.g. giving a message of progress, error notification, or to force immediate update of a data set's graphical representation. The tool manager loads the DLLs and makes them accessible for the front ends. The tool manager also facilitates the call of existing tools, e.g. to run a tool out of another one. The GUI uses this feature e.g. to read data file formats that are not generically supported by SAGA, for projecting geographic coordinate grids to be displayed in a map view, and to access and manipulate data through a database management system. Furthermore, this possibility of executing any loaded tool is used for the processing of tool chains. Tool chains are comparable to the models created with ArcGIS ModelBuilder (ESRI, 2015) or QGIS Processing Modeler (QGIS Development Team, 2014), but unlike these, SAGA does not yet include a graphical tool chain designer. Tool chains are defined in a simple XML based code that is interpreted by the tool chain class, another variant of the general tool class. This code has two major sections. The first part comprises the definition of the tool interface, e.g. the tool's name, description and a list of input, output and optional parameters. The second is a listing of the tools in the desired execution order. Tool chains are

Gelöscht: to response to mouse click in a map at a certain position

Gelöscht: data base

Gelöscht: it is a core mechanism for the tool chain class an efficient way to create new tools based on existing ones and perform exactly like hard coded tools. Since it is possible to create a tool chain directly from a data set history, a complex workflow can be developed interactively and then be automated for the analysis of further data sets.

2.2 General purpose tools

Besides more specific geoscientific methods, SAGA provides a wide range of general purpose tools. Since SAGA has a limited generic support for data file formats, the group of data import and export tools is an important feature to read and write data from various sources and store them to specific file formats supported by other software. Within this group a toolset interfacing the Geospatial Data Abstraction Library (GDAL) should be highlighted (http://www.gdal.org) (Bivand, 2014). The GDAL itself provides drivers for more than 200 different raster and vector formats, and therefore the SAGA API's data manager automatically loads unknown file formats through the GDAL by default.

A powerful alternative to file based data storage is provided by database management systems (DBMS), which offer the possibility of querying user defined subset selections. Various DBMS can be addressed with a toolset based on the Oracle, ODBC and DB2-CLI Template Library (OTL, http://otl.sourceforge.net). A second toolset allows accessing PostgreSQL databases (http://www.postgresql.org) and supports direct read and write access for vector and raster data, as provided by the PostGIS extension for spatial and geographic objects (http://postgis.net).

Gelöscht: offered

Gelöscht: data base

Gelöscht: data bases

Tools related to georeferencing and coordinate systems are indispensable for the work with spatial data. Particularly the coordinate transformation tools make use of two alternative projection libraries, the Geographic Translator GEOTRANS (http://earth-info.nga.mil/GandG/geotrans), and the Cartographic Projections Library PROJ.4 (http://trac.osgeo.org/proj/).

Due to SAGA's original focus on raster data analysis, numerous tools are available addressing this field, comprising tools for map algebra, resampling, and mosaicking. Nevertheless, the toolsets related to vector data also cover common operations such as overlays, buffers, spatial joins, and selections based on attributes or location. Overlay operations like intersection, difference, and union utilize the functions provided by the polygon clipping and offsetting library Clipper (http://sourceforge.net/projects/polyclipping). Besides, various methods for raster-vector and vector-raster conversions are available including contour line derivation and interpolation of scattered point data.

2.3 Graphical user interface

In order to apply SAGA tools for geoprocessing, a front end program is needed, which controls tools and data management. SAGA's GUI allows an intuitive approach to the management, analysis, and visualization of spatial data (Figure 7). It interactively gives access to the data and tools management and is complemented by a map management component. General commands can be executed through a menu and a tool bar. More specific commands for all managed elements, i.e. tools, data, and maps, are available through context menus. The properties of the selected element are shown in a separate control. While the number and type of properties depend on the respective element, a group of settings and a description are common to all managed elements. In case of a tool for instance, the settings give control to input and output data selection as well as to further tool specific options, while in case of a data set it provides several options for visualization in maps. Maps are the standard way of geodata display and offer various additional features, including scale bars, graticules, printing, and clipboard copying. Supplementary data visualization tools comprise histograms, charts, scatter plots, and 3D views. Tools can be executed either from the tools manager or through the main menu's geoprocessing subgroup, where by default all tools can be found following submenu categories. Due to the large number of tools a find and run command is a supplementary option to conveniently access all tools. In summary the GUI is a good choice for interactive work on a single data selection with immediate visualization. However, if complex work flows are applied repeatedly to numerous data sets, alternative front ends with scripting support are certainly more suitable.

Gelöscht: Figure 4

Gelöscht: Summarizing,

[Figure 7: Graphical user interface]

Gelöscht: Figure 5

2.4 Scripting and integration with other systems

The SAGA command line interpreter (CLI) is used to execute SAGA tools from a command line environment without any visualization or data management facilities. Therefore, the file paths for all input and output data have to be specified within the command. The CLI enables the creation of batch or shell script files with subsequent calls of SAGA tools to automate complex work flows and automatically apply them to similar data sets. Furthermore, the CLI allows calling SAGA tools from external programs in an easy way. This feature is used by the RSAGA package, which integrates SAGA tools with the R scripting environment (Brenning, 2008). Likewise, the Sistema EXTremeño de ANálisis TErritorial (SEXTANTE) makes SAGA tools accessible for various Java based GIS programs (gvSIG, OpenJUMP). In 2013 SEXTANTE was ported to Python to become a functional addition to QGIS (QGIS Development Team, 2014), another popular free and open source GIS software, thus spreading SAGA tools amongst many more GIS users. Alternatively to CLI based scripting, the SAGA API can also be accessed directly from Python. This connection is generated by means of the Simplified Wrapper and Interface Generator SWIG (http://www.swig.org) and provides access to almost the complete API. While this allows higher level scripting, the CLI remains easier to use for most purposes.

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Another option of integrating SAGA is direct linkage of the API. A very recent development is the integration of SAGA by the ZOO-Project (http://zoo-project.org/), which is a framework for setting up Web Processing Services (Fenoy et al., 2013). MicroCity (http://microcity.sourceforge.net) is a branch of SAGA, which adds support for the script programming language LUA, and has been used for city road network analyses (Sun, 2015). Laserdata LiS is proprietary software, mainly a toolset extension for the work with massive point data from LiDAR prospection (http://www.laserdata.at).

Table 1 summarizes the third party software mentioned above and underlines that SAGA is recognized first of all as geoprocessing engine. Only MicroCity and LiS make at least partly use of SAGA's GUI capabilities.

[Table 1: Software utilizing SAGA.]

Software	**Interface**	**Remarks**
QGIS	CLI	Processing Modeler
gvSIG	CLI	SEXTANTE
OpenJUMP	CLI	SEXTANTE
R	CLI	RSAGA
ZOO	API	Web Processing Service

MicroCity	API	LUA Extension
Laserdata LiS	API	Proprietary software

3 Review of SAGA related studies and applications

Due to its plethora of tools, covering a broad spectrum of geoscientific analysis and modeling applications and its user friendly environment, SAGA has been increasingly utilized for the processing of geodata, the implementation and calibration of statistical and process based models in various fields, and the visualization of results. The following chapter provides an overview of studies using SAGA in selected geoscientific fields, which were identified as major applications of the software. However, due to the vast number of studies this chapter only gives an outline without any claim to comprehensiveness. An overview is given in Table 2.

Gelöscht: modules

[Table 2: Studies utilizing SAGA in various research areas.]

Research area	***Studies***
Digital Terrain Analysis and Geomorphology	
DEM preprocessing (SRTM, ASTER, LiDAR)	Wichmann et al., 2008; Köthe and Bock, 2009; Peters-Walker et al., 2012
Debris flow analysis and modelling	Wichmann and Becht, 2005; Wichmann, 2006
Glacier mapping	Bolch, 2006; Bolch and Kamp, 2006
Fluvial sediment transport	Haas, 2008; Haas et al., 2011; Morche et al., 2012; Sass et al., 2012
Rockfall analysis and modelling	Wichmann and Becht, 2005; Wichmann, 2006; Wichmann and Becht, 2006; Fey et al., 2011; Haas et al., 2012; Heckmann et al., 2012
Landslide analysis and modelling	Günther, 2003; Günther et al., 2004; Varga et al., 2006; Brenning, 2008; Mantovani et al., 2010; Muenchow et al., 2012; Jansen, 2014
Avalanche analysis and modelling	Heckmann et al., 2005; Heckmann, 2006; Heckmann

	and Becht, 2006
Geomorphographic mapping	Köthe et al., 1996; Bock et al., 2007; Wehberg et al., 2013
Topographic indices	Grabs et al., 2010
Digital soil mapping	
Predictor variables	Böhner et al., 2002
Prediction of continuous soil properties	Bock and Köthe, 2008; Böhner and Köthe, 2003; Kidd and Viscarra Rossel, 2011; Kühn et al., 2009; Lado et al., 2008; Russ and Riek, 2011; Schauppenlehner, 2008
Prediction of soil classes	Bock, Michael et al., 2007; Roecker et al., 2010; Willer et al., 2009
Soil erosion (water)	Böhner and Selige, 2006; Enea et al., 2012; Milevski, 2008; Milevski et al., 2007; Patriche et al., 2012; Setiawan, 2012
Soil erosion (wind)	Böhner et al., 2002
Landslide	Brenning, 2008
Landscape modelling	Bock et al., 2011
Climatology and Meteorology	
Local deterministic interpolation	Fader et al., 2012;
Geo-statistical interpolation	Böhner, 2006, 2005, 2004; Gerlitz et al., 2014b; Kessler et al., 2007; Soria-Auza et al., 2010
Global interpolation techniques	Böhner and Antonic, 2009; Soria-Auza et al., 2010; Bolch, 2006; Dietrich and Böhner, 2008; Kessler et al., 2007; Lehrling, 2006; and Stötter and Sailer, 2012;
Statistical downscaling	Böhner, 2006, 2005, 2004; Weinzierl et al., 2013; , Böhner, 2006; Gerlitz et al., 2014a; Klinge et al., 2014; .
Numerical modelling	Nothdurft et al., 2012.; Böhner et al., 2013; Gerlitz, 2014;

Remote Sensing and image processing	
Remote sensing of forest cover and individual trees	Bechtel et al., 2008, Kamlisa et al., 2012; Phua et al., 2008
Vegetation mapping	Jürgens et al., 2013
Detection of glaciers and flow structures	Brenning, 2009, Bolch, 2006, 2007, Brenning et al., 2012
Roughness parameterisation	Bechtel et al., 2011
Annual Cycle in surface temperatures	Bechtel, 2015; Bechtel et al., 2012a; Bechtel and Schmidt, 2011
Urban climate modelling	Bechtel et al., 2012a; Bechtel and Schmidt, 2011
Classification of local climate zones	Bechtel, 2011; Bechtel et al., 2012b, 2015; Bechtel and Daneke, 2012
Downscaling-schemes of land surface temperature	Bechtel et al., 2012c; Bechtel et al., 2013
Estimation of air temperatures	Bechtel et al., 2014
Delineation of rock forming minerals in thin sections	Asmussen, 2014
Miscellaneous	
Vegetation-geography	Marini et al. 2007, Marini et al. 2009, Vanselow and Samimi 2011
Environmental studies	Böhner et al., 2002 Heinrich and Conrad 2008, Liersch and Volk 2008
Archaeology	Bock and Köthe, 2008; Böhner and Köthe, 2003; Kidd and Viscarra Rossel, 2011; Kühn et al., 2009; Lado et al., 2008; Russ and Riek, 2011; Schauppenlehner, 2008 Bernardini et al. 2013, Kaye 2013, Leopold et al. 2011
Miscellaneous	Bock, Michael et al., 2007; Roecker et al., 2010; Willer et al., 2009

3.1 Digital Terrain Analysis and Geomorphology

SAGA is a successor of three applications that were designed for digital terrain analysis, namely SARA, SADO, and DiGeM and up to today, the analysis of DEMs has remained a major focus. SAGA provides a comprehensive set of tools ranging from the preprocessing of

DEMs (e.g. filtering and filling procedures) through the generation of simple first and second order terrain derivatives, such as slope and curvature, to more sophisticated and process oriented terrain parameters, e.g the altitude above the channel network, the relative slope position or the SAGA-wetness index. The strong focus of SAGA in this particular field is distinctly reflected by its frequent utilization. This section gives a brief overview of available methods, applications, and studies with a special focus on the preprocessing of raw data, the derivation of terrain based predictor variables for statistical modeling approaches, the classification of distinct geomorphographic units and the implementation of suitable tools for specific investigations. For further information on principles and applications in terrain analysis including some of the methods that are implemented in SAGA, we refer to Wilson and Gallant (2000). Olaya and Conrad (2009) provided an introduction to geomorphometry in SAGA.

3.1.1 Preprocessing of raster data

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Filtering of bare ground from radar interferometry or laser scanning datasets is a pre-requisite for many applications. In order to make these datasets applicable for geomorphic and hydrologic analyses, SAGA offers tools to reduce elevation of forest canopies in radar based DEMs (SRTM) and to identify and eliminate man-made terrain features in laserscanning based datasets (Köthe and Bock 2009). Wichmann et al. (2008) created Digital Terrain Models (DTM) from airborne LiDAR data in different grid-cell sizes and investigated the effect on the simulation results of a debris flow model. DTM preparation included several processing steps such as morphological filtering and surface depression filling. The implementation of the debris flow model used in this study was described in Wichmann and Becht (2005) and Wichmann (2006). Peters-Walker et al. (2012) used SAGA and the Laserdata Information System, a software extending SAGA’s point cloud data management and analysis capabilities (Petrini-Montferri et al., 2009; Rieg et al., 2014), to derive a high-resolution DTM from LiDAR data. SAGA was subsequently applied to prepare all relevant catchment and channel network information to finally model discharge and bedload transport with the hydrologic model SimAlp/HQsim. In order to investigate climate and glacier changes from DEM and imagery data, Bolch (2006) and Bolch and Kamp (2006) proposed methods on glacier mapping from SRTM, ASTER and LANDSAT data. SAGA was used for DEM pre-processing, including import, projection and merging of data, as well as gap filling, curvature calculation and cluster analysis. Sediment transport in a proglacial river was

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investigated by Morche et al. (2012). The authors measured suspended sediment load and bed load along the river and quantified surface changes of sediment sources by comparison of multi-temporal terrestrial and airborne laser scanning data. LiDAR data, both airborne and terrestrial, were investigated by Haas et al. (2012) to quantify and analyze a rockfall event in the Western Dolomites. Volume, axial ratio and run-out length of single boulders were derived from the point clouds and statistically analyzed. Furthermore, the surface roughness in the run-out zone of the rockfall was estimated based on point cloud data. The authors also proposed approaches on how to use the derived surface roughness with a rockfall simulation model and compared the simulation results for different rock radii and both airborne and terrestrial laser scanning derived surface roughness datasets.

3.1.2 Using terrain analysis for the derivation of predictor variables

Gelöscht: :

Assuming that topographic characteristics are important drivers of various regional and local scale geodynamic processes, derivational terrain parameters are frequently utilized as predictor variables in statistical modeling applications. The close cooperation of the SAGA developer team with varying research projects resulted in the implementation of distinct terrain parameters, particularly suitable for specific investigations.

Targeting on the derivation of a spatial map of landslide risk, Varga et al. (2006) used a certainty-factor analysis including datasets of slope, curvature, land use, geology and primary dipping. Mantovani et al.(2010) proposed a new approach for landslide geomorphological mapping, using SAGA for tasks like DTM interpolation, slope and aspect calculations and the delineation of watersheds and stream network. Heckmann et al. (2005) and Heckmann (2006) investigated the sediment transport by avalanches in alpine catchments. Besides quantitative field measurements, SAGA was utilized to implement a spatial model of geomorphic avalanche activity. Potential initiation sites were delineated with a Certainty-Factor model (Heckmann and Becht, 2006). Process pathways were modelled by a random walk model, while run-out distance was calculated with a 2-parameter friction model. The simulation results (flow height, flow velocity and slope) and field measurements were finally used in a discriminant analysis to establish an empirical relationship. As an example of statistical geocomputing combining R and SAGA in the RSAGA package, Brenning (2008) presented a landslide susceptibility analysis with generalized additive models. It was shown that several local as well as catchment-related morphometric attributes are important, mostly non-linear, predictors of landslide occurrence. In a later study (Muenchow et al., 2012), RSAGA was employed to estimate geomorphic process rates of landslides along a humidity gradient in the tropical Andes.

3.1.3 Terrain Classification

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The usage of terrain (or landform) units allows providing soil scientists with conceptual spatial entities that are useful for mapping. The border lines of landform units highlight changing landform conditions that are frequently used to explain changing soil conditions. The classification concept of geomorphographic maps (Köthe et al., 1996) utilized DTM derivatives generated with SAGA. Locally adjusted thresholds of terrain parameters such as the SAGA wetness index, altitude above channel network, slope, relative slope position and terrain classification index for lowlands (Bock et al., 2007) divide a DTM in main classes along a gradient from the relative bottom (bottom areas mostly corresponding with valley floors) to the relative top (summit areas corresponding with crests, peaks and ridges) of the terrain, with slopes and terraces as intermediate classes. This semi-automated terrain-based landscape structure classification is also useful for the analysis of physical and ecological settings. Wehberg et al. (2013) derived geomorphographic units (GMUs) as discrete terrain entities on the basis of a SRTM digital elevation model with SAGA based terrain analysis. It was found that the GMUs reproduced the physiogeographic settings of the Okavango catchment appropriately and provided a basis for further mappings of vegetation or soil data. Brenning et al. (2012) investigated the detection of rock glacier flow structures by Gabor filters and IKONOS imagery. The authors used SAGA to calculate morphometric features like local slope, upslope contributing area, catchment slope, and catchment height. Also the all-year potential incoming solar radiation was computed. These terrain attributes were then used in combination with texture attributes for classification.

3.1.4 Implementation of specific tools

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The open source and modular architecture of SAGA easily enables the integration of new tools, if requested already available tools can be integrated. Thus several working groups utilize SAGA as a framework for specific analyses and modeling applications.

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Grabs et al. (2010) proposed a new algorithm to compute side-separated contributions along stream networks for the differentiation of the riparian zone and adjacent upland lateral contributions on each side of a stream. They implemented a new method SIDE (Stream Index Division Equations) in SAGA, which determines the orientation of flow lines relative to the stream flow direction and allows distinguishing between stream left and right sides. Haas (2008) and Haas et al. (2011) used a rule-based statistical model for the estimation of fluvial sediment transport rates from hillslopes and small hillslope channels. They introduced the concept of a "sediment contributing area", derived by terrain analysis, and implemented the algorithm in SAGA. The index was finally used in a regression model to derive sediment transport rates. The same model was applied in a later study concerning the impact of forest fires on geomorphic processes (Sass et al., 2012). Studying alpine sediment cascades, Wichmann and Becht (2005) and Wichmann (2006) implemented a rockfall model in SAGA. The model can be used to delineate the process area of rockfalls and for geomorphic process and natural hazard zonation by combining a random walk path finding algorithm with several friction models. Wichmann and Becht (2006) reviewed several rockfall models, implemented in SAGA. Three different methods for run-out distance calculation, an empirical model and two process-based models were compared in greater detail regarding their applicability for natural hazard zonation and the analysis of geomorphic activity. Fey et al. (2011) applied an empirical rockfall model (including the modeling of process pathway and run-out distance) for the back calculations of medium-scale rockfalls. Heckmann et al. (2012) integrated a modification of the rockfall model by Wichmann (2006) in order to re-calculate a rockfall event. Wichmann and Becht (2004) described the development of a model for torrent bed type debris flow, including the delineation of debris flow initiation sites, process pathway, as well as erosion and deposition zones. Potential process initiation sites were derived from channel slope, upslope contributing area, and the sediment contributing area. Pathway and run-out distance were modeled by combining a grid-based random walk model with a 2-parameter friction model. Zones of erosion and deposition were derived by threshold functions of channel gradient and modeled velocity. The model was validated with field measurements after a high magnitude rainstorm event. Recently, in an analytical study of the susceptibility of geological discontinuities for gravitational mass movements, Jansen (2014) applied geological engineering methods implemented in SAGA. The existing methodology (Günther, 2003; Günther et al., 2004) was thereby enhanced by interpolation routines available in SAGA which resulted in an increase of plausibility of the results.

3.2 Digital soil mapping

Digital soil mapping is one of the major applications in SAGA, which still reflects the initial focus of the software on developing terrain analysis methods for soil science. Due to its tool diversity, SAGA became a standard software package in the field, which is underlined by citations in relevant reviews and textbooks (Behrens and Scholten, 2006; Boettinger, 2010; Hartemink et al., 2008; Hengl and Reuter, 2009; Lal and Stewart, 2014).

According to McBratney et al. (2003) digital soil mapping generally is understood as a collection of methods for the estimation of spatial information on soils. These estimates can comprise specific soil properties (continuous data), entire soil types respectively soil associations (classified data), or the susceptibility of soil against certain soil threats. Based on existing point measurements and/or spatial data from other origin, so called predictor variables (sometimes referred to as covariates), digital soil mapping techniques can be applied in order to generate extensive soil information. The most important SAGA-specific predictor in the field of digital soil mapping is the SAGA wetness index (Böhner et al., 2002), which is derived from a DTM and reflects the theoretical distribution of lateral water accumulation.

Several studies determine a correlation between one or more soil properties and spatial predictor variables. Russ and Riek (2011) derived groundwater depths from SAGA covariates with the help of pedo-transfer functions. Other authors used statistical methods to model soil parameters, e.g. to apply a multiple regression model for the derivation of groundwater depths (Bock and Köthe, 2008). A more sophisticated regression model was developed by Kühn et al. (2009), who explained the spatial distribution of several soil parameters, such as soil organic carbon or carbonate content, by means of interpolated apparent electrical conductivity data and DEM covariates.

A number of studies refer to SAGA implemented geostatistical methods in order to derive soil parameters. Böhner and Köthe (2003) combined geostatistical regionalization (Kriging) of grain size fractions with pedo-transfer functions to develop a whole set of physical soil properties. Schauppenlehner (2008) and Lado et al. (2008) used regression Kriging to estimate the distribution of heavy metals in surface soils at European scale. Schauppenlehner (2008) compared different geostatistical methods for spatial estimation of soil quality values (Ackerzahl) while Kidd and Viscarra Rossel (2011) tested numerous derivatives from DEM and remote sensing data as covariates for the geostatistical modeling of soil properties. Further, SAGA based predictor variables can be used to directly model the distribution of classified data of soil types or soil associations by (external) machine learning algorithms such as Random Forest (Roecker et al., 2010) or Classification Tree (Willer et al., 2009). Besides, SAGA offers internal classification routines, such as the statistical cluster analysis, which was applied to combine DEM covariates to serve as a conceptual soil map (Bock et al., 2007).

Extensive work has been done to model the spatial distribution of soil threats. In addition to the mentioned study on heavy metal distribution in European soils (Lado et al., 2008), several studies estimated soil degradation caused by erosion using SAGA routines. Besides the attempt to record existing soil degradation from erosion with the help of covariates (Milevski, 2008; Milevski et al., 2007), a particular focus is the evaluation of soil erosion risk using the SAGA revised slope length factor (Böhner and Selige, 2006) based on the empirical universal soil loss equation (Wischmeier and Smith, 1978). Patriche et al. (2012) and Enea et al. (2012) are further examples for studies dealing with this issue. Recently, SAGA was extended by a process-based soil erosion model (Setiawan, 2012). The model WEELS allows wind erosion modeling based on SAGA routines (Böhner et al., 2002). The vulnerability towards landslides was modelled using a combination of SAGA and the statistical package R (Brenning, 2008; Goetz et al., 2011).

The SAGA landscape evolution model (SALEM) is rather between the disciplines of Geomorphology and Soil Sciences. The SALEM (Bock et al., 2012) was designed for simulating processes that comprise the *critical zone* (National Research Council, 2001) and depicts the landscape elements in a process-oriented and time-dynamical way.

3.3 Climatology and Meteorology

Historically, climatology and meteorology are probably the natural science disciplines where most of the epistemological progress was based on the spatially explicit analysis of local observations. Indeed, the ingenious inventions of climate measuring instruments since the late 16th century by Galileo Galilei, Evangelista Torricelli, Otto von Guericke, and others would have rarely contributed to this enormous scientific progress since the late 18th century, if instrumental observations had not been taken from different locations, enabling a ‘synoptic’ analysis of spatial climate variations. Today, core functionalities of contemporary GIS, e.g. a range of basic spatial analysis routines are well suited for this systematic examination of climate variations over space, typically applied to infer spatially continuous (gridded) climate layers from point source observations. Especially for this purpose of climate spatialization, SAGA is equipped with numerous tools, ranging from interpolation methods (local, global

Gelöscht: and modules

and regression based regionalization) to complex surface parameterization techniques, supporting both, statistical and numerical climate modeling.

Interpolation methods: Although SAGA provides an almost complete collection of local and global interpolation techniques, comprising of deterministic (Inverse Distance Weighted, Local Polynomial, Radial Basis Functions), and in particular geostatistical Kriging methods and its derivatives (e.g. ordinary, universal, regression Kriging), interpolation techniques have rarely been used as a standalone method in climate spatialization (Fader et al., 2012). Instead, these methods were frequently combined with more complex statistical or numerical climate modeling approaches, using e.g. ordinary Kriging, thin-plate spline or inverse distance weighted for the interpolation of model residues, in order to obtain a correction layer for the adjustment of modeling results (Böhner, 2006, 2005, 2004; Gerlitz et al., 2014b; Kessler et al., 2007; Soria-Auza et al., 2010; Weinzierl et al., 2013).

Regression based regionalization: In topographically structured terrain and especially in high mountain environments, where the often low density and non-representative distribution of met-stations leads to unsatisfying interpolation results, statistical methods utilizing explanatory fields (e.g. DEM elevation and its first and second order partial derivatives) as statistical predictors are distinctly preferred in climate spatialization. In order to achieve a proper estimation of the deterministic, topographically determined component of climate variations, SAGA provides a set of DEM-parameters, explicitly constructed to represent orographically induced topoclimatic effects. A comprehensive explanation and justification of DEM-based measures for the parameterization of prominent topoclimatic phenomena, such as the anisotropic heating and formation of warm zones at slopes, cold air flow and cold air potentials, orographic effects on rainfall variations and wind velocities, and terrain determined alterations of short- and longwave radiation fluxes, is given in Böhner and Antonic (2009). Soria-Auza et al. (2010) conducted a systematic evaluation of SAGA based climate spatialization results in comparison with Worldclim data (Hijmans et al., 2005), highlighting the advantages of SAGA based surface parameterization methods and its added values for ecological modeling applications. Further spatialization results from mountainous modeling domains in Asia, Europe and South America are presented in Bolch (2006), Dietrich and Böhner (2008), Kessler et al. (2007), Lehrling (2006) and Stötter and Sailer (2012).

Numerical and statistical modeling: Fostered by advanced computational capacities on the one hand, and increasingly free available topographic data sets on the other, regression based techniques evolved to a common standard in climate spatialization since the 1990s. The results, though often with high spatial resolution, however, are most commonly static representations of mean (monthly, seasonal or annual) climate values. Whilst to date, the temporal high resolution, dynamical representation of climate processes and values remains a domain of high performance computing based climate modeling, rarely covered by GIS. To overcome this disadvantage, Böhner (2006, 2005, 2004) introduced a SAGA-based climate spatialization approach, which basically merges statistical downscaling and surface parameterization techniques. Assuming the spatiotemporal variability of a climatic variable to be predominantly controlled by both, tropospheric and terrain-forced processes, different DEM parameters and monthly resolution tropospheric fields from NCAR-NCEP or ERA interim reanalyses had been considered as statistical predictors, supporting a monthly resolution estimation of climate variables for Germany (Böhner, 2004), the Okavango catchment (Weinzierl et al., 2013) and different modeling domains in Central and High Asia (Böhner, 2006; Gerlitz et al., 2014a; Klinge et al., 2014). In order to allow a dynamical representation of numerical climate simulations via SAGA, most recently, an efficient climate model interface has been realized, which enables to import and process even complex and vast climate model outputs. Resulting options for climate spatialization and its advancements in terms of applicability, precision and temporal resolution, using daily and sub-daily resolution ERA-interim reanalysis as dynamic forcings for statistical downscaling are presented in Böhner et al. (2013) and Gerlitz (2014). Daily resolution values of climate variables for Baden-Württemberg on a 50 m x 50 m grid were derived by a SAGA based downscaling approach, refining Regional Climate Model (RCM) simulations of present-day climates and IPCC A1B and A2 climate scenarios, supporting the quantification of climate change effects on forest site index for major tree species (Nothdurft et al., 2012).

Climate layers performed with SAGA, however, are seldom stand-alone results but mostly considered as basic predictor variables or driving forcings for further environmental analysis and modeling. Applications range from paleoclimate reconstructions (Aichner et al., 2010; Böhner and Lehmkuhl, 2005; Herzschuh et al., 2011, 2010; Wang et al., 2014) over environmental resource assessment and regionalization (Böhner and Kickner, 2006; Böhner and Langkamp, 2010; Kessler et al., 2007; Klinge et al., 2003; Lehmkuhl et al., 2003; Miehe et al., 2014; Soria-Auza, 2010) to climate impact assessment and soil erosion modeling (Böhner, 2004; Böhner et al., 2003; Böhner and Köthe, 2003; Conrad et al., 2006).

3.4 Remote Sensing and image processing

SAGA offers a large number of scientific methods and tools for multispectral, hyperspectral and thermal remote sensing, including geometrical preprocessing and spectral filtering techniques, multispectral and Fourier-transformations, supervised and unsupervised classification algorithms, change detection, as well as segmentation methods for object oriented image analysis (Blaschke, 2010). The filtering techniques include standard linear bandpass-filters (Gaussian, Laplacian, user defined), nonlinear filters (majority, rank, and the morphological filters dilation, erosion, opening, closing, morphological gradient, top hat, and black hat). Besides different vegetation indices, tasseled cap transformation, sharpening techniques for multi-sensor data and principal component analysis for feature reduction are implemented. Available classifiers comprise k-means (unsupervised), binary encoding, parallelepiped, minimum and Mahalanobis distance, maximum likelihood, spectral angle mapper, decision trees, random forest, support vector machines, artificial neural networks, as well as ensemble based classifiers while region growing and watershed algorithms are available for image segmentation. Besides, some tools are available for the processing of data from specific sensors, like calibration to reflectance and generation of cloud masks for Landsat data. Further, SAGA offers great possibilities to process LIDAR point data (c.f. section 3.4). The code of the remote sensing and image processing tools is partly based on free libraries and open source software including OpenCV (Open Source Computer Vision, http://opencv.org/), ViGrA (Vision with Generic Algorithms, Köthe, 2000), LIBSVM (Chang and Lin, 2011) and GRASS GIS (Geographical Resources Analysis Support System) (Neteler et al., 2012).

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A number of remote sensing based studies using SAGA have been published in different fields. In forestry, multispectral remote sensing data from different times and sensors and fragmentation models were used to examine deforestation and fragmentation of peat swamp forest covers in Malaysia (Kamlisa et al., 2012; Phua et al., 2008). Bechtel et al. (2008) applied different segmentation algorithms to identify individual tree crowns in very high resolution imagery. Further, a new vegetation map of the Central Namib was produced by a supervised classification of remote sensing data from MODIS and ETM+ 7 in combination with other environmental parameters such as climatic and topographic data by Jürgens (2013).

In glaciology, SAGA remote sensing tools were used for the integration of different terrain datasets into a combined topographical and multispectral classification of rock glaciers (Brenning, 2009) to analyze the decrease in glacier cover in Kazakhstan (Bolch, 2007, 2006) and to detect flow structures in IKONOS imagery (Brenning et al., 2012). Recently, several remote sensing studies successfully applied SAGA to generate surface parameters for local scale climatic mapping and analysis in urban areas. In (Bechtel et al., (2011) digital height models from interferometric synthetic aperture radar data were established to derive roughness parameters and anemometric characteristics of urban surfaces while the thermal properties were investigated regarding the annual cycles of surface temperatures (Bechtel, 2015, 2012, 2011a). Further, the urban surface parameters were implemented for urban climatic modeling applications (Bechtel et al., 2012b; Bechtel and Schmidt, 2011) and the classification of local climate zones (Bechtel, 2011b; Bechtel et al., 2015, 2012a; Bechtel and Daneke, 2012). Additionally, SAGA was utilized to develop downscaling-schemes for land surface temperature from geostationary satellites to spatial resolutions of up to 100 m (Bechtel et al., 2012c; Bechtel et al., 2013) and to estimate in situ air temperatures (Bechtel et al., 2014).

Gelöscht: (Bechtel, 2012, 2011a)

Gelöscht: (Bechtel et al., 2012a; Bechtel, 2011b; Bechtel and Daneke, 2012)

The image processing capacities also rouse interest in other disciplines. Asmussen et al. (2015) developed a workflow for petrographic thin section images, which comprises the delineation of rock forming minerals and data acquisition of various fabric parameters. The method is based on SAGA's seeded simple region growing algorithm to obtain flexible and precise object detection for any occurring mineral type in weathered sub-arkose sandstone material, and benefits from a reproducible and transparent GIS database.

Gelöscht: (2014)

3.5 Miscellaneous

Besides its core applications, such as terrain analysis, geomorphometry, soil mapping and climate spatialization, SAGA has been used in numerous studies of very different fields and wide scope. One physical geographic sub-discipline, which should be outlined separately due to a series of recent publications, is biogeography and particularly plant geography. Marini et al. (2007) e.g. studied the influence of local environmental factors on plant species richness in the Alps. Different terrain attributes like elevation or slope were tested in statistical models besides other climatic or nutrient parameters, in order to explain biodiversity patterns on different alpine meadows. A similar approach was carried out by Marini et al. (2009) with focus on the impact of farm size and terrain attributes on insect and plant diversity of

Gelöscht: bio- resp. vegetation-geography managed grasslands in the Alps. Another example of a bio-geographic relevant application can be found in Vanselow and Samimi (2011), who preprocessed a DEM by means of the fill sinks method and afterwards derived terrain attributes, e.g. altitude above channel network and slope, in order to designate potential future pastures in Tajikistan. Other environmental studies comprise Heinrich and Conrad (2008), who applied a cellular automate approach on testing the simulation of flow and diffusion dynamics in shallow water bodies, and Czegka and Junge (2008), who used SAGA as a mobile field tool in environmental geochemistry research activities (GPS coupled navigation on lakes, in situ observation monitoring). Liersch and Volk (2008) implemented a metric conceptual rainfall-runoff model including calibration tools within the SAGA framework with the intention of flood risk prediction.

Besides geoscience, GIS products are increasingly utilized in various fields dealing with spatially explicit data. For example in archaeology Bernardini et al. (2013) investigated Airborne LiDAR derived images, in order to detect and to monitor hitherto unknown anthropogenic structures and archaeological sites in the Trieste Karst landscape. Leopold et al. (2011) likewise produced a DEM, based on LiDAR information, and subsequently derived a high resolution cross section with the objective to reveal the location of a former production site of bronze statues at the southern slope of the Acropolis of Athens. The approach was compared to other methods of demarcating prehistoric surface structures (e.g. magnetometry, electrical resistivity tomography, ground-penetration radar) and proved to be suitable as an additional archaeological reconstruction tool. Kaye (2013) utilized SAGA based terrain analysis, in particular the catchment water balance methodology and the implemented hydrological tools. By means of the GIS based approach, the author reconstructed historical water availability in South England as an important logistic factor for the Roman Army and contributed to finding the location of Boudica's last battle in 60 or 61 AD.

Finally, two very specific examples for the utilization of SAGA should be highlighted, which particularly indicate the wide scope of the software. Different spatial detection techniques of radioactive matter being randomly dispersed on a free area, were tested for the purpose of quantifying dose rates, surface activities, mass concentrations in aerosols and their temporal and spatial distributions (Prouza et al., 2010). Most peculiar, the morphometric investigation of chewing surfaces of animals should be emphasized, which was based on an automated analysis using specific interpolation and segmentation approaches (Czech, 2010).

4 Conclusions and outlook

Since the first public release in 2004, SAGA has very rapidly developed from rather specialized niche software for digital terrain analyses to a mature stage FOSS GIS platform, offering the entire spectrum of geodata analysis, mapping and modeling applications of contemporary GIS software. Right from the beginning, the multiple options of an object-oriented programming environment and the consequently modular organized architecture fostered the development of specific methods often distinctly beyond off-the-shelf GIS products. In the present version 2.1.4, SAGA offers more than 600 tools, much of them reflecting a leading paradigm in the SAGA development: Advancements in GIS development are only to be achieved, if the development is closely embedded in research processes. Indeed, in responding on scientific questions and needs, SAGA is not only a research supporting tool but likewise its outcome, which complements related scientific publications with the ultimate documentation of used methodologies in the form of source codes.

Gelöscht: 700

Gelöscht: modules

Gelöscht: SAGA is not only a tool, which supports research but likewise the outcome, ultimately documented in source codes and scientific publications.

Today SAGA is maintained and enhanced at the Institute of Geography, Section Physical Geography at Hamburg University, however, a fast growing user community and developers all over the world contribute to the evolution by their specific needs and applications. For the near future support for multidimensional raster, e.g. addressing volumes, time series and hyperspectral data, as well as a stronger integration with DBMS like PostgreSQL/PostGIS are envisaged to broaden the application of SAGA. A further challenging field of the coming SAGA development will be the enhancement of tools and methods, supporting a scale-crossing amalgamation of climate and environmental modeling applications. Already today, SAGA enables an assimilation, dynamical representation and statistical downscaling of climate model outputs, required to interlink dynamical climate forcings with process models for case studies and climate impact analyses. By bridging both, spatial scales and scientific disciplines, SAGA responds on the steadily increasing needs for high quality, spatially explicit data and information, ultimately tracing GIS to its roots. Indeed, already in 1965, Michael F. Ducey and Duane F. Marble stated in the probably first written document, which used the term “Geographic Information System”, that "the primary function of a Geographic Information System is to make spatially oriented information available in a usable form." Happy 50th birthday GIS!

Acknowledgements

The authors would like to thank all SAGA developers for their contributions to the code and the documentation and numerous users for their valuable remarks. Further, we thank I. Friedrich for editorial support with the manuscript. Eventually, we thank Michael F. Ducey and Duane F. Marble for using the term “Geographic Information System” in their Technical Note “Some Comments on Technical Aspects of Geographic Information Systems” from 1965.

Code availability

The SAGA source code repository is hosted at http://sourceforge.net/projects/saga-gis/ using an Apache-Subversion (SVN) server as versioning and revision control system. Read only access is possible without login. A branch is provided for SAGA version 2.1.4, to which is referred to in this paper (release-2-1-4, revision 2335). Alternatively the source code for this version can be downloaded directly from the files section at http://sourceforge.net/projects /saga-gis/.

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