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Abstract: Glaciers are among the best terrestrial indicators of climate change and glacier inventories have attracted growing interest. In Italy, the first official glacier inventory was completed in 1925 and 774 glacial bodies were identified. As the amount of data continues to increase, and new techniques become available, there is a growing demand for computer tools that can efficiently manage the collected data.
The Research Institute for Geo-hydrological Protection of the National Research Council, in cooperation with the Departments of Computer Science and Earth Sciences of the University of Turin, created a database that provide a modern tool for storing, processing and sharing glaciological data. The database was developed that could store heterogeneous resources. A set of web search queries to retrieve the information was implemented. The adopted architecture is server-side and the software are open source. The website interface was to meet the needs of a distributed public. The interface usability is simple and intuitive. Through this interface, any type of glaciological resource can be managed, specific searches can be performed, and the results exported in a common format.
The use of a relational database to store and organize the vast variety of resources about Italian glaciers collected over the last century constitutes a significant step forward in ensuring the safety and accessibility of such data. Moreover, the same benefits also apply to the enhanced operability for handling information in the future, including new and emerging types of data formats such as geographic and multimedia files.
Future developments include the integration of cartographic data such as base maps, satellite images and vector data. The relational database described in this paper will be the heart of a new geographic system that will merge data, data attributes and maps with a complete description of Italian glacial environments.

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Title

An open source, web-based, relational database for studying glaciers in the Italian Alps

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Abstract

Glaciers are among the best terrestrial indicators of climate change and glacier inventories have attracted growing interest. In Italy, the first official glacier inventory was completed in 1925 and 774 glacial bodies were identified. As the amount of data continues to increase, and new techniques become available, there is a growing demand for computer tools that can efficiently manage the collected data.

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The use of a relational database to store and organize the vast variety of resources about Italian glaciers collected over the last century constitutes a significant step forward in ensuring the safety and accessibility of such data. Moreover, the same benefits also apply to the enhanced operability for handling information in the future, including new and emerging types of data formats such as geographic and multimedia files.

Future developments include the integration of cartographic data such as base maps, satellite images and vector data. The relational database described in this paper will be the heart of a new geographic system that will merge data, data attributes and maps with a complete description of Italian glacial environments.

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1. Introduction

Glaciers are among the best terrestrial indicators of climate change because of their sensitivity to climatic variations and visible growth and shrinkage (IPCC, 2007; Kaab et al., 2007). Glacier fluctuations are relevant for the impact they have on the surface water cycle (Braun et al., 2000; Kaser et al., 2010; Koboltschnig and Schöner, 2011), sediment fluxes (Stott and Mount, 2006;

Irvine-Fynn et al., 2011), and natural hazards (O'Connor and Costa, 1993; Clague and Evans, 2000; Kaab et al., 2005; Cossart et al., 2008; Chiarle et al., 2011).

For these reasons, glacier inventories (including current glacier extent and rates of change) have attracted growing interest (Fig. 1). Some of the longest series of observations of glacier fluctuations have been compiled by the Italian Glaciological Committee (Comitato Glaciologico Italiano, CGI). The first official glaciological survey of Italian glaciers was carried out in 1911. Since then, CGI voluntary surveyors have closely followed glacier evolution (Malaroda, 1995), documenting changes with annual measurement of terminus position, photographs, reports, and maps.

As the amount of data continues to increase, and new techniques for data acquisition and analysis become available, there is a growing demand for computer tools that can efficiently store, update, process and share the collected data (Baroni, 2010). Such applications need to take into account concerns about the peculiarity of Italian glaciers, as well as archival documentation management and the integration of existing digital global glacier inventories (Muller et al., 1977; Raup et al., 2007; NSIDC, 2011).

Since its beginning, Glacial Risks in Western Alps (GlaRiskAlp) project no. 56 under the 2007-2013 ALCoTra (Alpi Latine Cooperazione Transfrontiera, Franco-Italian Transborder Alpine Cooperation program) has addressed the need for compiling a complete inventory of Alpine glaciers within the interregional area which would enable researchers to examine criticalities and processes, focusing, for example, on glacier displacement in glacial and periglacial zones consequent to ongoing climate change. Under the project protocol, the National Research Council-Research Institute for Geo-hydrological Protection (Consiglio Nazionale delle Ricerche-Istituto di Ricerca per la Protezione Idrogeologica, CNR-IRPI), in cooperation with the University of Turin (Departments of Computer Science and Earth Sciences), created a database to meet the project's specific needs and to provide a modern tool for storing, processing and sharing glaciological data. Besides meeting the routine requirements for data organization, retrieval and sharing, the database was designed to accommodate the historical CGI data and new data acquisition, collection and storage technologies. This paper illustrates the structure, functions, and potential use of the database.

2. Geographic context and type of data

We studied Italian glaciers in the European Alps. This range was selected for developing a relational glacier database because it is by far the world's best known mountain area in terms of weather, climate and related environmental characteristics (Barry, 1994). Geographically, the European Alps sweep in an arc extending from the Mediterranean (French and Italian Riviera) to the hilly areas of Austria and Slovenia. The Alps are bounded to the north by the Swiss and Bavarian Plateaux, to the south by the Po and Venetian Plains. As a whole, the Alpine range has an average ridge height of about 2 500 m, a length of 800 km, and a mean width of about 200 km (Frei and Schar, 1998). Based on their geomorphological features, three classical physiographical regions are distinguished: 1) the Western Alps, a relatively narrow N-S elongated arch at the Franco-Italian border, where Mount Blanc and the majority of the highest peaks are located; 2) the Central Alps, from Lake Geneva to the Grisons (Switzerland), where the range bends in an E-W direction; 3) the Eastern Alps, east of the Grisons, the largest complex of the chain, where the Southern Calcareous Alps fringe on the chain's northern core.

These classical physiographical regions show different orographic and hydrographic patterns depending on the interplay between geological and geomorphological factors. In the Central Alps, the main drainage network is mostly longitudinal to the chain with a few prominent valleys (e.g., the Valais and the Inn valleys), controlled by major tectonic discontinuities in the Alpine structure. On the margins, most valleys show a centripetal trend. In the Eastern Alps, the valleys run northwards or southwards onto the foreland; due to differential uplift, the remnants of ancient longitudinal segments have been incorporated into the present-day drainage system (Bosi, 2004). In the Western Alps, the mountain relief is intersected by a series of major transverse valleys that divide the range into numerous basement massifs characterized mainly by lower erodibility than in the surrounding rock units. Morphologically, cirque glaciers largely predominate over alpine-type valley glaciers.

From a long-term perspective of the area's geomorphological history, the onset of Quaternary glaciations in the Western Alps repeatedly and deeply modeled the Alpine relief, with regional features of contrasting competent rocks and high uplift and denudation rates. Holocene deglaciation later reduced the number of glaciers and the surface area they once covered, which led to gravitational and fluvial/torrential processes resulting in widespread instability phenomena (Soldati et al., 2006).

From today's perspective, for obvious reasons of exposure and orography, the southern/eastern flank of the Alps (corresponding to the Italian Alps) has far fewer glaciers than the northern side. Based on an inventory of Alpine glaciers dating from the 1970s (Haeberli et al., 1989), the 1 368 Italian glaciers account for 27% of the total number and cover an area of 602 km^2 (21% of the total glacierized Alpine area). Most (80% of the total) are small. Ranked by size, 651 glaciers are in the lowest category (0.1-0.5 km^2), with 508 covering less than 0.1 km^2; 89 (17.7% of the total) are in the next higher category (0.5-1 km^2); 99 (1-5 km^2) and 17 (5-10 km^2) in the next higher categories, respectively. Only 4 extend over 10 km^2: the Miage Glacier (Mont Blanc) and the Lys Glacier (Monte Rosa) in the Western Alps; the Forni Glacier (Ortles-Cevedale) and the Mandrone Glacier (Adamello-Presanella) in the Central Alps. Most of the Italian glaciers are concentrated at the highest elevations of the eastern (mainly the Rhaetian and Norian Alps) and western regions (mainly the Graian and Pennine Alps).

In addition to elevation, local climatic situations influence the distribution of glacierized areas in the Italian Alps, owing mainly to the relationship between glacier size and position and the source and propagation of masses of humid maritime air (Calmanti et al., 2007). It is clear, therefore, that a more detailed interpretation of their present-day distribution and typology could be achieved with an updated glacier inventory.

The first inventory of Italian glaciers was completed in 1925, when 774 glacial bodies were identified and located (Porro, 1925; Porro and Labus, 1927); the original forms report numerical and alphanumerical characteristics of each glacier. The inventory was later updated, coinciding with the 1957-58 International Geophysical Year, and developed in collaboration between the CGI and the National Research Council: 838 existing glaciers and 190 extinct ones were mapped and briefly described (CNR-CGI, 1959). From then onwards, geographic, topographic and morphologic data have been added, yet the records and database remain incomplete, particularly as regards glacier surface area. National inventory updates carried out in the following decades have never been published (Secchieri, 1985; Ajassa et al., 1997). What information there is on current glacier conditions has been provided by local initiatives (Galluccio and Catasta, 1992; Regione Autonoma Valle d’Aosta, 2011).

On a global scale, there are two glacier inventories that report information about Italian glaciers. The World Glacial Inventory (WGI) lists information on over 100 000 glaciers throughout the world. The inventory parameters include geographic location, area, length, orientation, elevation and classification of morphological type and moraines (Haeberli, 1989). The Global Land Ice Measurements from Space (GLIMS) project monitors the world's glaciers primarily using data from optical satellite instruments (e.g., the Advanced Spaceborne Thermal Emission and reflection Radiometer, ASTER). GLIMS is a cooperative effort involving over sixty institutions world-wide with the goal to inventory the majority of the world’s estimated 160 000 glaciers. GLIMS maintains a geospatial database available via a website featuring interactive maps and a interoperability standard web mapping service.

Yet for all the apparent gaps, the history of Italian glaciers over the past century is remarkably well documented. Every year since 1911, volunteer CGI surveyors visit the glaciers, measure the terminus position and take pictures from fixed points; in addition, they write reports on the general conditions of the glaciers and the main changes observed, as well as the occurrence of relevant phenomena (e.g., rockfall, lake growth). The survey results appear annually in the CGI journal (CGI, 2011), which was first published in 1914 under the title *Bollettino del Comitato Glaciologico Italiano*. A valuable source of information, the journal has long been the mainstay reference for Italian glaciological studies. In 1978, the journal changed name to *Geografia Fisica e Dinamica Quaternaria*, when its objectives were extended to include studies in geomorphology, physical geography and quaternary geology.

Besides the data from annual surveys, the CGI archives also contain aerial and terrestrial photos, topographic surveys and maps, thematic maps, mass balances, journals, books, and unpublished studies. In recent years, however, data type and format have changed dramatically: digital photos, orthophotos and satellite images, shape files, digital terrestrial models (DTMs) and global positioning system (GPS) points are rapidly replacing the traditional documentation formats.

As the GlaRiskAlp project continues, new glaciological data for the areas involved in the project are being acquired, along with historical documentation from archives and libraries other than those of the CGI. Geomorphological studies are under way to reconstruct glacier evolution since the end of the Little Ice Age and to update the values of their principal morphometric parameters (e.g., surface, length, altitude). Finally, the use of modern data and geographic information system (GIS) tools has permitted the acquisition of more accurate and detailed data on glacial bodies and their recent evolution.

3. Description of the system

The main goals that have shaped the design and implementation of the computer-based inventory described in this paper are the following:

1) to archive and store the huge amount of glaciological data collected by the CGI and other agencies and to plan for new types of data and data formats in current use;
2) to develop a tool that could catalogue the data sources for each glacier according to technological standards and requirements of the major existing international glacier databases;
3) to share the collected data, making it accessible and useful for various purposes;
4) to meet the above-mentioned demands with low-cost solutions.

After a careful analysis of these requirements, we have decided to proceeded as follows: 1) a relational database was designed and created that could store and catalog copious and heterogeneous information and resources (in paper and digital format) and their interrelationships; 2) the design of the database was based on the data set documentation of the WGI and a set of rilevant web search queries to retrieve the information and resources was designed and implemented; 3) the adopted architecture was server-side with user level access regulated by six privilege levels; and 4) the choice fell to the use of open source software.

The implemented system consists of a relational database and a web interface (see the next sections); it was developed on a Microsoft Windows Server 2003 operating system on top of WAMP (Apache 2.2.4, MySQL 5.0.45 and PHP 5.2.4) open source solutions. A javascript jQuery framework that exploits Ajax technology and Web 2.0 principles was also integrated (Nuzzi, 2011). Data persistence is guaranteed by a RAID 5 server configuration with 3 hard disks and by daily backups through an external NAS unit.

3.1 Design and structure of the relational database

Despite its complexity (59 tables), the high-level structure of the database schema is relatively simple and easy to understand (Fig. 2). The schema is centered on a table representing the main concept of the domain of interest, namely, the glacier. Around this table are several other tables containing additional information related to the glaciers. A special set of tables is devoted to the management and tracking of end-user access to the database.

The additional tables are partitioned into six groups:

- *location*, *orographic info*: information on glacier location and orographic classification
- *glaciological surveys & mass balances*, *morphologic/metric info*: information on the morphologic characteristics of the glaciers, as well as historical information on morphometric characteristics and other measurements taken by human operators
- *attachments*: information on external files containing documents and other digital data regarding the glaciers
- *users*: information on end-user access to the database

The purpose of the *glaciers* table is to provide basic information about each glacier and to link it to the additional information held in the other tables. The main attribute of *glaciers* for the identification of each glacier is *glac_cgi_cod*, whose value is a unique standard code assigned by the CGI (CNR-CGI, 1959). Each glacier is also identified by its primary (and secondary) name, as well as by a unique code assigned to it by the WGI (*WGI_cod*).

The *glaciers* table contains additional basic information, such as whether the glacier is *extinct* or not (and when), and its regional code and classification. This table (like most of the other tables in the database) tracks bookkeeping information on who inserted/last modified each record and when.

As mentioned, the remaining attributes are links (foreign keys) to additional information listed in other tables (see below).

The *location* tables are further partitioned into: *administrative* tables which specify locations in terms of geopolitical entities (*county*, *province*, *region*, *country*); the *geographic* table specifies location in terms of geographic coordinates; and the *basins* table specifies a sequence of basins that connect the glacier with the sea. Each glacier can be linked to several different records in an administrative table (e.g., a glacier spanning two counties), and with a sequence of basins and a set of geographic coordinates.

The *orographic info* tables are used for the orographic classification of the glaciers within the Alps, according to both the Traditional and the Suddivisione Orografica Internazionale Unificata del Sistema Alpino (International Standardized Mountain Subdivision of the Alps, SOIUSA) systems (Marazzi, 2005). The *Traditional classification* consists of a three-tiered hierarchy (from the top: *parts*, *sections*, *groups*), while the *SOIUSA classification* consists of a seven-tiered hierarchy, plus a parallel five-tiered hierarchy. Overall, 15 tables are necessary to store the hierarchies. Each glacier is linked to exactly one record at the bottom tier of each of the two main hierarchies.

The *campaigns & mass balances* tables contain data collected from *signals* and *photographic stations* installed near the glacier (CGI glaciological surveys), as well as data collected during *mass balance*s. Specifically, the *measures* taken during glaciological campaigns refer to the changes in the glacier terminus, while the *mass balances* refer to the changes in the glacier mass.

In general, a glacier is linked to several different signals and stations. Since the tables in this group contain historical data, each signal and photographic station can be linked to measures taken on different days, months and/or years. Similarly, a glacier is linked to several mass balances performed at different multiannual periods of time.

The *morphologic/metric info* tables contain the morphologic characteristics of the glaciers, such as the *form*, the *frontal characteristic* and the *longitudinal profile*, as well as the measurement of morphometric characteristics such as *area*, *altitude* and *thickness*. Each glacier has a unique value for a given morphologic characteristic. Because a glacier's morphometric characteristics can change with time, the glacier can be associated with several measures of the same morphometric characteristic. Similarly, several *activities* of the terminus, corresponding to different years, can be associated with a glacier.

The *attachments* tables contain information about text *documents*, pictures (including *terrestrial photos* and *aerial photos*) and cartographic data stored in digital files on the local file system and/or on remote computers. Such files can be of any kind, e.g., a text document in *pdf*, a *jpg* image or a *drg* (Digital Raster Graphic) map.

Each record in the tables of the group provides basic information about a specific attachment, such as the *author*, *editor* and date of publication of a scientific book, or the textual description of the *subject* of a photo. Most importantly, each record points to the file *path* and/or *URL* where the file containing the attachment resides, allowing end-users to access its content.

Each attachment can have links (not shown in the figure) to the *campaigns & mass balances* tables, making it possible, for example, to specify the glaciological campaign treated in a text document.

Finally, the *users* tables contain information on database users and their access time. Each user is given an *access level* which can be used to limit the set of operations allowed on the data (see next section).

The bookkeeping information also includes descriptions of official *projects* during which the data on the glaciers were collected and entered into the database, and tracks the participation of the users in such projects.

3.2 Web interface

The Italian Alpine Glacier Inventory (IAGI) website was designed and developed to meet the needs of a diversified and distributed public. The interface design is simple and intuitive with a high level of usability. The server-side architecture permits access to the IAGI from any given point in the network through the use of a common web browser. The website comprises 306 pages, structured into two distinct sections: Database management and Search the entire glacier inventory. The first is subdivided into two levels: one for data entry and the other for data modification. The second section contains the pages in which users can carry out database searching. In order to query the database and retrieve relevant information, 54 predefined web search queries were created. These are grouped under Glacier (10), Geography (8), Morphology (25), Glaciological Survey (4) and Management (7). With these queries users can browse the entire database and focus the search on a specific resource type (Table 1).

Through this website interface any type of acquired glaciological resource can be archived and managed (paper or digital format), specific searches performed (on one or more glaciers, by Alpine range sector, by hydrographic basin, by administrative criteria), and the results printed and exported in a common format (PDF, CSV, JPEG).

The database access has six different login levels for each user assigned by the administrator.

1. Basic search (access to metadata, query and report print out);
2. Advanced search (access to metadata, access to digital resources, query, and report print out);
3. Basic use (access to digital resources, data entry and management, query, print out and exportation of results);
4. Glaciological operator use (data entry and management of resources related to glaciological surveys, access to digital resources, data entry and management, query, print out and exportation of results);
5. Advanced use (data entry and management of all resources in the database, access to digital resources, data entry and management, query, print out and exportation of results);
6. Administrator (full access)

The advantages to having six different access levels are that the IAGI can be used by many different kinds of users simultaneously and that the database management is kept simple and versatile. The IAGI website is available at http://dbirpi.to.cnr.it/db_cgi/index.php (Italian version, an English version is planned in the near future).

4. Discussion

The integrated database and web interface system was designed and developed to meet clearly defined goals (see section 3). Thanks to the choice of well established open-source, standard-based technologies, both the database and the web interface could be implemented with low set-up cost without compromising on reliability and quality.The use of a relational database to store and organize the vast variety of information and resources about Alpine glaciers collected by the CGI over the last century constitutes a significant step forward in ensuring the safety, reliability, scalability and accessibility of such data. Moreover, the same benefits also apply to the enhanced operability for handling information in the future, including new and emerging types of data formats such as geographic and multimedia files.

Another important benefit is that, thanks to its flexibility and comprehensiveness, the database makes it possible to envision future extensions and new applications for enriching, analyzing and extracting the information it contains (see next section for future research directions).

As concerns the IAGI web interface, we believe that its principal strength lies in its high level of flexibility – inspired by dynamic content management systems (DCMS) – wich permits the management of a wide range of type of resource and the creation of various different types of reports;

Two current weaknesses of the IAGI are:

1) a predefined query set that, while permitting faster data search operations, limits the range of information that can be retrieved according to narrow criteria, which may be frustrating for users;

2) the lack of a system that can visualize spatial data, although the georeferenced coordinates for each glacier are present in the database. Solutions for this latter issue are currently being sought.

5. Future work and conclusions

This work is an excellent starting point for the management of existing glaciological data. It must however be able to integrate cartographic data such as base maps, satellite images, vector data,

etc.etc.. the proposed relational database will be the heart of a new geographic system that will merge data, data attributes and maps with a complete description of glacial italian environment.
Future developments are being pursued along two lines of research: 1) ongoing collaboration with the CGI for the collection, analysis and cataloging of data recorded from the early 1900s to the present; and 2) through this joint collaboration, to create an infrastructure of spatial data to be associated with the current database with a view to enhance accessibility and exchange of information (maps and attributes) about Italian glaciers.

In recent years, the Ministry of the Environment and Protection of the Land and the Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare (MATTIM) is placing its infrastructure of web-based services at the disposal of local agencies in a strategic move to promote and disseminate the use of geographical data and to make environmental and land-use information available to a wider public, including the general public, in connection with national and European projects and initiatives. Through collaboration with the CGI and the Ministry of the Environment the web-based services can be utilized, uniting the information retrieved from the CGI database with those accessible from the national geoportal.

The first step is to collect data in digital format, organize and then disseminate the data amassed since the CGI started collecting records, the bulk of which is either not yet accessible or difficult to work with because not interoperable. Specifically, the idea is to create a glaciological geoportal connected to the Ministry of the Environment that will enable access to descriptive data about glaciers and the measurements taken during glaciological surveys and those derived from orthoaerophotography or satellite imaging. The project will be set up according to an infrastructure of spatial data with an architecture that conforms to the principles and standards set forth by the Infrastructure for Spatial Information in Europe (INSPIRE) initiative. The glaciological geoportal will allow users to conduct research on metadata provided by the project partners and to visualize the data published by the partners' services.

All the databases will be implemented or interfaced with instruments that support the standard Open Geospatial Consortium (OGC) interfaces such as the open source software program PostGIS and the PostgreSQL relational database. The georeferenced data will be accessible through the OGC's web map services (WMS) and web feature services (WFS). Maps can be dynamically created using the WMS spatially referenced data derived from geographic information (Fig. 3). This international standard defines a map as a representation of geographic information, producing a digital image that can be visualized with a web browser.

The interesting aspect of this solution resides in the MapServer's capability to integrate in real time local data (from geographic files and/or dbms) with remote data retrieved from servers compatible with the WMS standard, thus achieving full data interoperability.

The function flow chart may be summarized as follows:

- Map request: the user sends the request to the remote MapServer though the web interface;
- Access to local data: the CGI MapServer collects local data held on typical storage systems for geographic data (filesystem and/or geographic rdbms);
- WMS layer request: the CGI MapServer requests from the remote server at the Ministry one or more geographic layers though a WMS protocol standardized by the OGC and the ISO;
- Fusion of the layers: the MapServer integrates the data (local and remote) to create the final map.

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Figure captions

Fig. 1. Galambra Glacier (Valle di Susa, Italy) WGI code: I4L01471002, CGI code: 26. A) Picture postcard postmarked 3 May 1954 (courtesy of G. Mortara). B) Photograph taken on 8 August 2009 (courtesy of F.M. Tron).

Fig. 2. Structure and database schema.

Fig. 3. Schematic diagram of geographic interchange data based on OGC/ISO Web Map Service (WMS). From Ministero dell'Ambiente e della Tutela del Territorio e del Mare, modified.

Table captions

Table 1. List of the search queries. >, related to; (), number of queries for this search.

Table 1

Glacier	Geography	Morphology	Glaciological survey	Management
List of the glaciers	Glaciers > municipality	Glaciers > morphology (7)	Fluctuations > glacier	Project list
Glacier report	Glaciers > province	Glaciers > morphometry (2)	Fluctuation > glacier > year	Glaciers > project
Glaciers > extinct	Glaciers > region	Glaciers > aspect (16)	Mass balances > glacier	Project > start date
Glaciers > operators	Glaciers > country		Mass balance > glacier > year	Projects > manager
Glaciers > compiler	Glaciers > effluent			Glaciers > user
Glaciers > attach. (5)	Glaciers > tributary			Accesses > user
	Glaciers > orographic classification (2)			Delete glacier

Figure(s)

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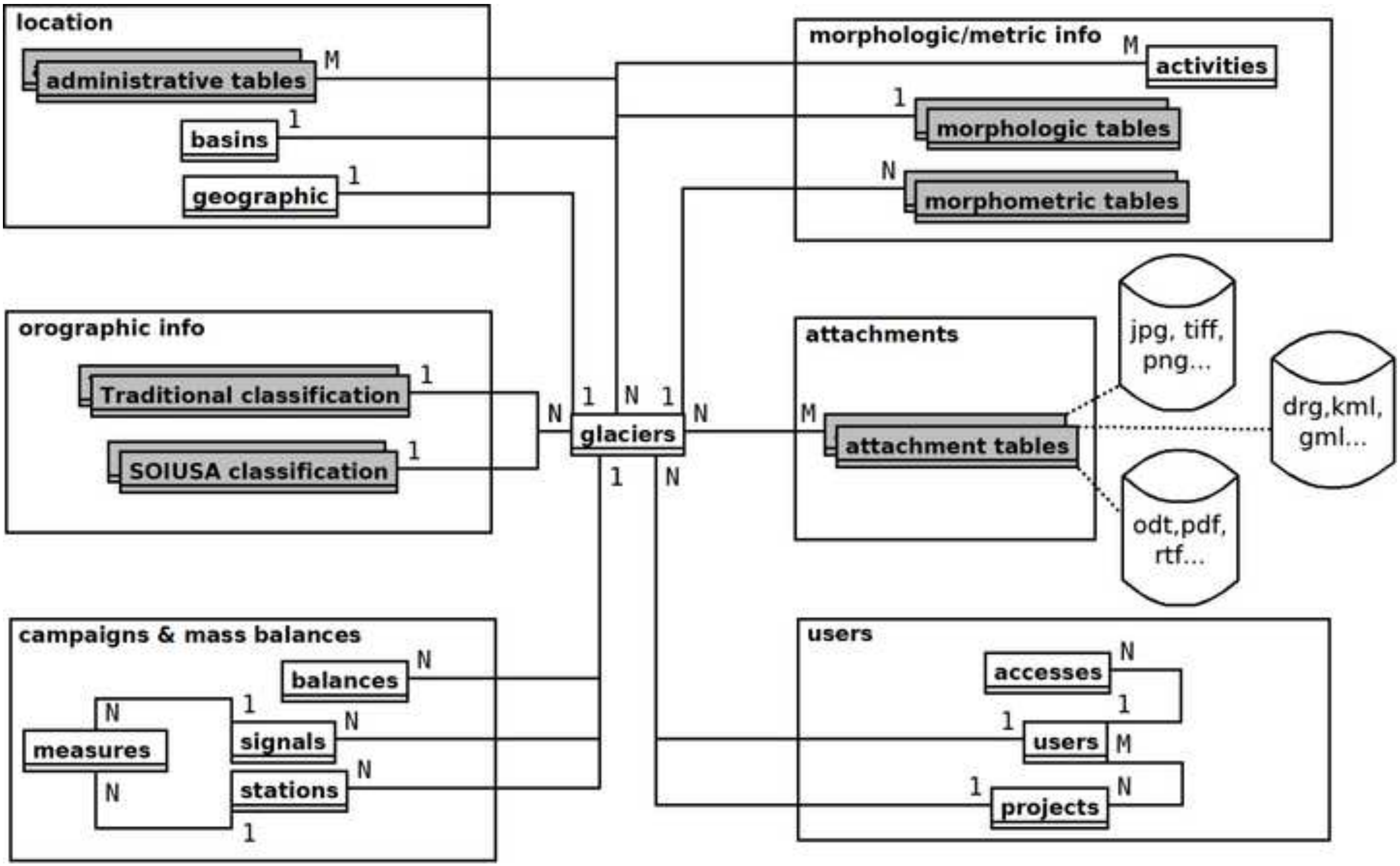

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