Determining geometric links between glaciers and lakes on the Tibetan plateau

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ABSTRACT

The Tibetan plateau and surrounding mountain ranges contain the largest amount of ice outside the polar region. The Tibetan plateau also contains more than one thousand lakes and is the origin of a large part of the water resources of South and East Asia, the most densely populated regions on earth. Recent studies concluded that the glacial area on the Tibetan plateau and surroundings has decreased significantly in the last decades. To directly assess changes in glacial mass balance from remote sensing data is challenging in this area because of the high relief and the relatively small size of the thousands of different glaciers. Recently however, trends for glacier elevation change in the Himalaya Mountain Range could be estimated based on terrain elevation profiles captured by ICESat.

In addition to glacier changes, in recent research lake level changes on the Tibetan plateau were observed as well. Water level changes of several big Tibetan lakes have been monitored for the last decade by in-situ measurements and/or satellite radar / laser altimetry data. As an interesting result, about 150 lake level trends on the Tibetan plateau between 2003 and 2009 were obtained using ICESat laser altimetry. In fact, water level changes of a Tibetan lake are caused by direct precipitation, snow melt, glacial melt, moisture conditions, evaporation and rainwater runoff. Thus, clearly interpreting these lake level trends on a large region as Tibet is still a challenge in future.

In this study, we exploit different remote sensing products to explicitly create links between Tibetan glaciers, lakes and rivers. Main data sources consist of the so-called CAREERI glacier mask, a lake mask based on the MODIS MOD44W water product and the HydroSHEDS river network product derived from SRTM elevation data. Based on a drainage network analysis, we first differentiate between lakes with and without outlet and then all drainage links between glaciers and lakes are determined all over the Tibetan plateau. The results show that 25.3% of the total glacier area directly drains into one of 244 Tibetan lakes. Consequently, dependency of a Tibetan lake on glacial runoff is defined as the ratio between the total area of glaciers draining into a lake and the area of the catchment of the lake. These dependencies are determined for all ~900 Tibetan lakes over one kilometer square. This result indicates which lakes are expected to be strongly affected by the predicted further shrinkage of the glaciers on the Tibetan plateau. Geometric links between Tibetan glaciers and lakes in this analysis are expected to strongly assist in understanding the often very local differences in lake level change patterns and in total this indirect methodology could turn out in a new way to better constrain local glacial mass balance variations in this climate-sensitive region.

This paper gives an overview of methodology and results as presented in HESSD [18]. Here however, we do give more details on the implementation of the workflow in a GIS environment, by specifying how exactly the different input data products are combined in terms of GIS layers in order to obtain the required output data.

KEYWORD: Tibetan plateau, lake level change, glacial runoff, geometric link

1. INTRODUCTION

Recent studies concluded that the glacial area on the Tibetan plateau and surroundings has decreased significantly in the last decades. The glacier shrinkage has occurred at many studied areas all over Tibet, as demonstrated in [1, 2, 3]. Besides, the glaciers have also retreated in the inner plateau [4], and in the Mt. Qomolangma Region of the Himalayas [5]. Using satellite laser altimetry and a global elevation model, Kaab [6] quantified the glacial thinning in the Hindu Kush-Karakoram-Himalaya region from 2003 to 2008. Moreover, Gardelle [7] also revealed that ice thinning and ablation is occurring at high rates in the central Karakoram and the Himalaya mountain ranges, based on the difference between two digital elevation models between 1999 and 2008. These glacier reductions will directly affect lake and river water levels on the Tibetan plateau and surroundings.

In addition to glacier changes, in recent research lake level changes on the Tibetan plateau were observed as well. As described in [8, 9], about 150 water level trends of the Tibetan lakes sampled by the ICESat/GLAS LIDAR campaigns between 2003 and 2009 were estimated. Some large lakes on the Tibetan plateau were also monitored by radar altimetry and/or by in-situ measurements, e.g. Nam Co, Qinghai and Seilin, as described in [10, 11, 12, 13].

In general, water level changes of a Tibetan lake are caused by direct precipitation, snow melt, glacial melt, moisture conditions, evaporation and rainwater runoff. Krause [12] applied a hydrological system model for the Nam Co Lake basin to determine the lake level dependency on temperature, evaporation, precipitation and glacier runoff. In addition, Zhang [4] studied the relation between river runoff and glacier runoff caused by loss of ice mass in the Tuotuo River basin. At the moment these types of studies are only possible for individual lakes or river basins, simply because necessary measurements are not available for most part of the Tibetan plateau. What is possible however as demonstrated in this paper is to geometrically link all Tibetan lakes to glaciers. This enables to determine for each lake its geometric dependency on glacial runoff.

2. METHODS

In this section, firstly we introduce the input data, described as GIS layers and their origins. Then we design the output data, also as GIS layers, representing geospatial objects such as outlets, links from glaciers to lakes, and links between lakes. It is also shown how to create these layers. Finally an indicator for the dependency of a Tibetan lake on glacial runoff is determined.

2.1. Input data

Main data sources used in this paper are the MODIS land-water mask, the CAREERI glacier mask, and the HydroSHEDS river network and drainage basin data. The water mask determines the locations of the Tibetan lakes. The glacier mask gives the outlines of the Tibetan glaciers. The river data provides information on the direction of surface runoff, while the drainage basin data describes the catchment areas or the watershed boundaries on the Tibetan plateau. The river network is used to analyze the geometric links between glaciers and lakes. To integrate them, all these data are stored into the GIS shapefile vector format, as illustrated in Figure 1, and are projected onto the WGS84 Geographic Coordinate System.

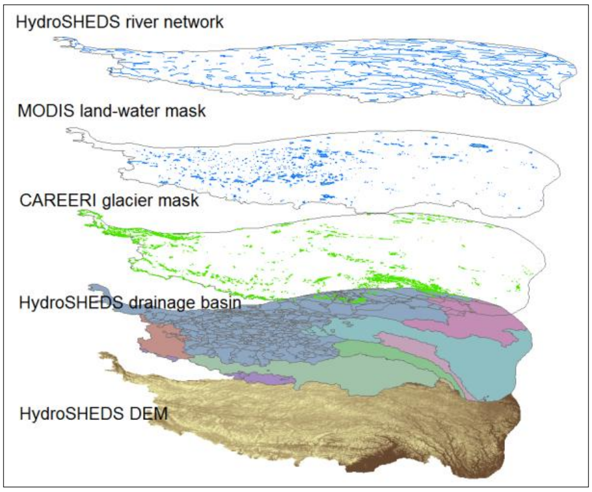

Figure 1. The input data consists of the CAREERI glacier mask, the MODIS land-water mask and the HydroSHEDS river network and drainage basin data.

Lake layer

The Tibetan lakes were derived from the MODIS land-water mask, called MODIS MOD44 W 250 m, as described in [14]. The lakes were stored in polygon vector format and its designed attributes include an identification code (Lake_ID) and a surface area in kilometer square (Area_km2). In this study, all 891 lakes over one kilometer square on the Tibetan plateau were considered. The lake layer is noted as a table in the relative database, *Lakes (Shape, Lake_ID, Area_km2)*, and each record is corresponding to a lake.

Glacier layer

The glaciers on the Tibetan plateau were extracted from the CAREERI glacier mask. This glacier inventory was based on observed data of the glaciers from 1978 to 2002, as reported in [15], in which the original data was collected and digitized by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science (CAREERI). The glacier layer was exported in polygon vector format and it attributes include an identification code (Glacier_ID) and a glacier surface area in kilometer square (Area_km2). In summary, the glacier layer contains 34,676 glaciers on the Tibetan plateau. The glacier layer is noted as a table in the relational database, *Glaciers (Shape, Glacier_ID, Area_km2)*, and each record is corresponding to a glacier.

River layer

The rivers, presenting the drainage network on the Tibetan plateau, were extracted from the river data of the Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS), as described in [16] (Lehner et al, 2006). This product is built at 15 arc-second resolution (approximately 500m at the equator) from the drainage direction layers, derived from elevation data of the Shuttle Radar Topography Mission (SRTM). The river layer was exported in polyline vector format and it attributes consist of the length of each river segment in kilometers (Length) and a number of grid cells corresponding to the total number of inflowing cells (Up_cells). Each polyline is formed by a from-node (or a starting point), a list of ordered vertices and a to-node (or an ending point), presenting the direction of the river segment. Figure 2 shows the river network inside the Kekexili catchment where the direction of each river segment is symbolized by an arrow. The river layer is noted as a table in the relative database, *Rivers (Shape, Length, Up_cells)*, and each record is corresponding to a river.

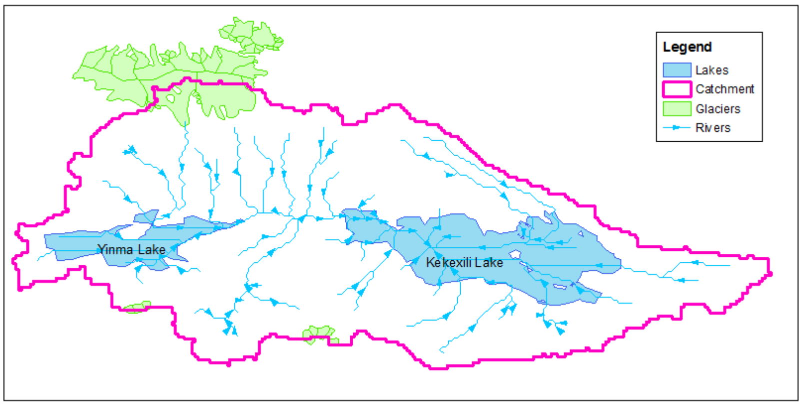

Figure 2. The river network with directions of river segments inside the Kekexili catchment

Catchment layer

The catchments were extracted from the HydroSHEDS drainage basin data. This product, describing the catchment areas or the watershed boundaries, is also built at 15 arc-second resolution. The catchment layer was stored into the polygon vector format, for example in Figure 2 the catchment contains Kekexili lake and Yinma lake. Its attributes consist of a catchment area in kilometer square (Area_km2), an identification code corresponding to the major river basin which each catchment belongs to (Basin_ID), and a name of the corresponding basin (Basin_name) such as Brahmaputra, Ganges, Indus, Mekong, Yangtze, Yellow River, etc. The catchment layer is noted as a table in the relative database, *Catchments (Shape, Area_km2, Basin_ID, Basin_name)*, and each record is corresponding to a catchment.

2.2. Output data

The output data are expected to represent connections between glaciers and lakes, and subsequently to estimate how much a lake depends in a geometric way on glaciers. Vector layers are used to indicate outlets, links from a glacier to a lake, and links between lakes.

Outlet layer

An outlet is a single point, where the water joins another water body such as a lake, river, ocean, etc, as described in [17]. The outlet of a lake catchment, also called a sink, can be a point where water is lost underground. The outlet layer is designed as a GIS shapefile formatted in points where each point represents the outlet of a lake catchment. Its attributes consist of an identification code of the corresponding lake (Lake_ID), the area of a lake catchment in kilometer square (AC_km2) and a code to distinguish between an outlet and a sink (Code). For example, the code value 0 corresponds to an outlet, while the code value 1 corresponds to a sink. The outlet layer is noted as a table in the relational database, *Outlets(Shape,Lake_ID,AC_km2,Code)*, and each record is corresponding to an outlet of a lake catchment.

Based on the river network and the location of a lake, the outlet of each lake has to be inside the lake region. If river segments all stream to the outlet inside the lake, the lake is a sink of a closed catchment. If one river segment leaves the lake and drains to another lake or river, the lake is not a sink. For example, sink A, sink B and outlet C are determined as illustrated in Figure 3.

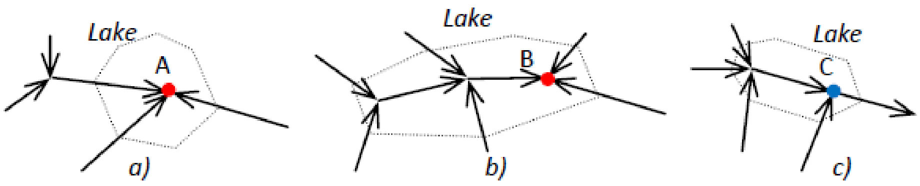

Figure 3. a) Sink A, b) Sink B, and c) Outlet C

Lake-lake link layer

A geometric link from one lake to another represents a stream flow on the terrain surface. The lake-lake link layer is designed as a GIS shapefile formatted as polyline vector. Its attributes include the identification code of the from-lake or a source (FLake_ID), the identification code of the to-lake or a destination (TLake_ID) and the length of the stream flow in kilometer. The lake-lake link layer is noted as a table in the relational database, *LL_Links(Shape,FLake_ID,TLake_ID,Length),* and each record is corresponding to a geometric link between lakes.

According to the characteristics of a drainage river network, each river segment is an oriented vector and at each node of the river network, either no or one river segment leaves the node, as illustrated in Figure 4. Thus each geometric link is determined as an oriented route of river segments from the outlet of a lake catchment to the outlet of another lake catchment. For example, the links among the outlets A, B and C are determined as the route AB and the route BC, as shown in Figure 4.

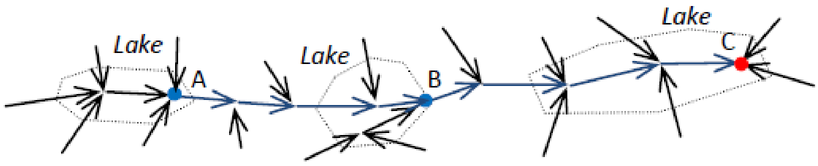

Figure 4. The oriented routes from the outlet A to the outlet B, and from the outlet B to the sink C

Glacier- lake link layer

A geometric link from a glacier to a lake represents a glacier-melting flow on the terrain surface. The glacier-lake link layer is designed as a GIS shapefile in the form of a polyline vector. Its attributes consist of the identification code of a glacier (Glacier_ID), the identification code of a lake (Lake_ID), and the area of the glacier in kilometer square (Area_km2). The glacier-lake link layer is noted as a table in the relational database, *GL_Links(Shape,Glacier_ID,Lake_ID,Area_km2),* and each record is corresponding to a geometric link from a glacier to a lake.

Similarly to the lake-lake links, each glacier-lake link is determined as an oriented route of river segments. In this case, however, the source of the stream flow is a glacier, not a lake, so it is necessary to find a point, as a node of the river network, representing the origin of glacier outflow. In this study, the representative source of the route is assumed to be one node of a river segment which is nearest to the glacial outline. In the GIS computation, the distance from a glacier to a representative source is the minimum distance from the point to a vertex of the polygon. For example, the distances from glacier G1 to nodes A, B and C are d_{G1A}, d_{G1B} and d_{G1C} and similarly the distances from glacier G2 to nodes B and C are d_{G2B} and d_{G2C}, as illustrated in Figure 5. Subsequently, as distance d_{G1B} is minimal, node B is assumed to be the origin of the glacier melt drainage G1.

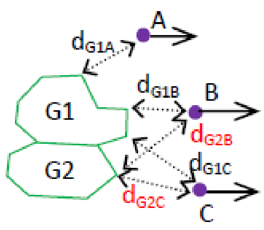

Figure 5. The from-nodes B and C are corresponding to the origins of the glacier melt drainage G1 and G2

According to the characteristics of outlets, lake-lake links and glacier-lake links, the module which we have built in the GIS environment results in an outlet layer, a lake-lake link layer, and a glacier-lake link layer all in the form of shapefiles. For example the output data created at the Kekexili catchment is shown in Figure 6.

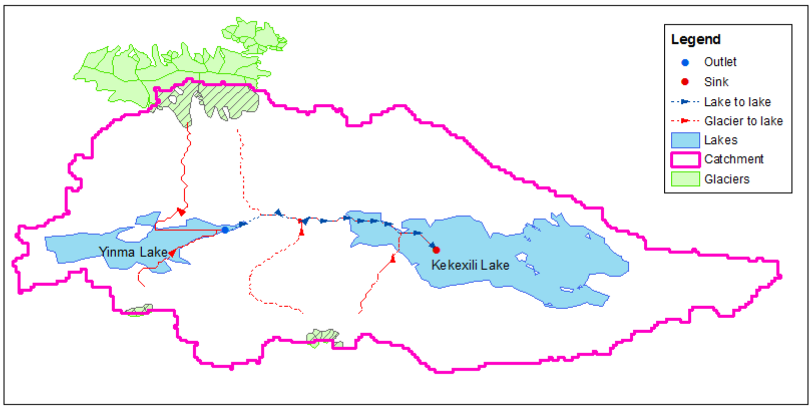

Figure 6. The output data represent connections from glaciers to Yinma Lake and Kekexili Lake, and the route from Yinma Lake to Kekexili Lake

2.3. Geometric dependency of a lake on glacial runoff

Indicator R_D, the geometric dependency of a lake on glacial runoff, is defined as the ratio between the total area of glaciers directly draining to a lake and the lake's catchment area, as indicated in [18]. If the ratio equals zero, the lake catchment doesn't contain any glaciers, meaning that the lake is not fed by glaciers at all. If the indicator is close to one, the lake catchment is almost fully covered by glaciers.

$$R_D = \frac{A_{GD}}{A_C}$$

$$A_{GD} = \sum_i A_i$$

$$A_C \approx N * D$$

Here A_{GD} is the total area of directly contributing glaciers to the lake, and A_C is the lake catchment area. A_i is the area of the ith glacier directly draining to the lake. N is the total number of accumulated grid cells draining into the outlet of the lake catchment, and D is the size of the grid cell at the outlet location, approximately using the ‘haversine’ formula [19].

3. RESULTS

As a result, the glacier-lake link layer represents the melting drainage from glaciers to Tibetan lakes. Based on the spatial distribution of glaciers and catchments, the glacier area per catchment is computed as shown in Table 1. In this case only the major catchments of the Tibetan plateau are considered. Table 1 also indicates that 25.3% of the total glacier area directly drains to one of the 244 lakes. In the inner plateau, 37.4% of the glacier area directly drains to one of 160 lakes, mostly situated in the north and the northwest of the inner plateau. For the catchment of the Brahmaputra River, 11.1% of its glacier area directly drains into one of its 33 lakes while the rest of glaciers of approximate 14,000 km^2 drain into Brahmaputra River, passing through China, India and Bangladesh. Similarly, approximate 316 km^2 of glaciers drain to streams which form the origins of Mekong River, supporting fresh water for China, Myanmar, Laos, Thailand, Cambodia and Vietnam.

Table 1. Glacier area per basin on the Tibetan plateau. A_{Total} is the total area of glaciers with direct runoff in a lake and R_{Total} is the ratio between the total area of glaciers with direct runoff in a lake and the catchment area.

No.	Basin name	Basin area (km^2)	Total glacier area (km^2)	No. of directly glacier-fed lakes	A_{Total} (km^2)	R_{Total} (%)
1	Brahmaputra	344 528	15 677	33	1 748.2	11.1
2	Ganges	39 772	3 636	10	355.5	9.8
3	Indus	101 428	2 430	14	727.9	30.0
4	Irrawaddy	4 227	32	0	0.0	0.0
5	Mekong	86 392	327	2	11.0	3.4
6	Salween	108 266	1 893	4	53.4	2.8
7	Yangtze	484 317	2 432	18	520.0	21.4
8	Yellow River	263 928	297	3	167.1	56.4
9	Inner plateau	1 098 382	26 512	160	9 909.7	37.4
	Total	2 531 240	53 236	244	13 492.8	25.3

Subsequently, the R_D indicator, the geometric dependency of a lake on direct glacial runoff, is determined for all Tibetan lakes. The R_D indicators are symbolized by red disks in Figure 7. The grouping of the Tibetan lakes by level of the R_D geometric dependency on directly contributing glaciers is also performed. Accordingly, most of the lakes have an R_D indicator under 0.005, corresponding to 75% of lakes with at least one glacier draining directly into it. The result also indicates that eight lakes have an R_D value of over 0.5. These eight lakes are all relatively small, occupying each approximately 2 km^2. They are obviously located near glaciers and spread along mountain ranges in the southern and western Tibetan plateau.

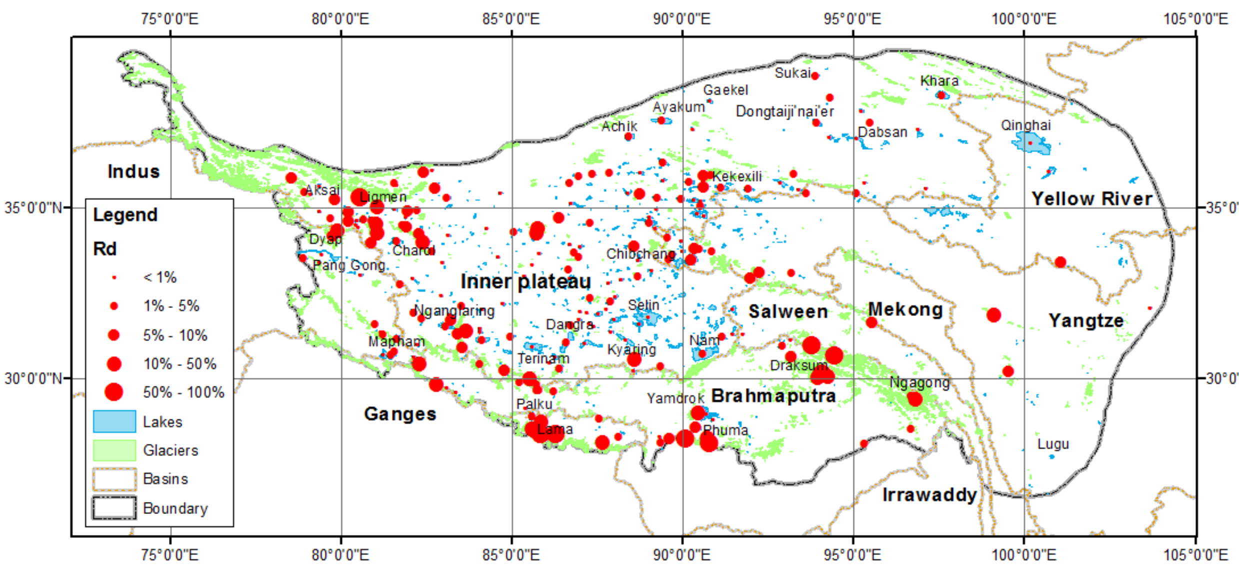

Figure 7. The geometric dependency R_D of Tibetan lakes on direct glacial runoff

In addition to being directly fed by glaciers, the lake-lake link layer indicates that a Tibetan lake can be fed indirectly by glaciers through other upstream lakes. Accordingly, there are 13 lakes with runoff and 9 sinks, which are indirectly fed by glaciers but not directly.

4. CONCLUSIONS

Based on a drainage network analysis, the geometric links between glaciers and lakes is determined for the complete Tibetan plateau. The results indicate that 244 lakes depend on directly contributing glaciers and 266 lakes depend on upstream glaciers. The ratio between the total area of glaciers draining into a lake and the area of its catchment is used to be representative for the dependency of a lake on glacial runoff. Although this geometric dependency is just a proxy for the actual dependency of a lake on glacial runoff, our results clearly list which lakes are more or less dependent on glacial runoff. Therefore our results indicate which lakes are expected to be strongly affected by the predicted further shrinkage of the glaciers on the Tibetan plateau.

5. ACKNOWLEDGEMENTS

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