Hydrology and Earth System Sciences Discussions

Geometric dependency of Tibetan lakes on glacial runoff

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Abstract

The Tibetan plateau is an essential source of water for South-East Asia. The run-off from its ~ 34 000 glaciers, which occupy an area of ~ 50 000 km^2, feed Tibetan lakes and major Asian rivers like Indus and Brahmaputra. Reported glacial shrinkage likely has its impact on the run-off. Unfortunately, accurate quantification of glacial changes is difficult over the high relief Tibetan plateau. However, it has been recently shown that it is possible to directly assess water level changes of a significant part of the ~ 900 Tibetan lakes greater than one square kilometer. This paper exploits different remote sensing products to explicitly create links between Tibetan glaciers, lakes and rivers. The results allow us first to differentiate between lakes with and without outlet. In addition, we introduce the notion of geometric dependency of a lake on glacial runoff, 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. To obtain these results, we combine 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, all drainage links between glaciers and lakes are determined. The results show that 25.3 % of the total glacier area directly drains into one of 244 Tibetan lakes. The results also give the geometric dependency of each lake on glacial runoff. For example, there are 10 lakes with direct glacial runoff from at least 240 km^2 of glacier. Three case studies, including one over the well-studied Nam Tso, demonstrate how the geometric dependency of a lake on glacial runoff can be directly linked to hydrological processes.

1 Introduction

The Tibetan plateau is the highest and largest plateau of the world, and stores a large amount of glaciers. It 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. According to Yao et al. (2012), systematic differences in glacier status are apparent from region to region, with the most intensive shrinkage in the Himalayas (excluding the Karakoram) charac-
terized by the greatest reduction in glacial length and area for the past 30 yr. Besides, Sorg et al. (2012) presented that glacier shrinkage has occurred at the Tien Shan Mountains in the north-west of Tibet during the period of 1950s to 2000s. Also as reported in Wang et al. (2011), 910 glaciers in the Middle Qilian Mountain Region have reduced in area rapidly from 1956 to 2003, with a mean reduction of $0.10 \, \text{km}^2$ per in-
dividual glacier. The glaciers have also retreated in the Tuotuo River basin, the source of Yangtze River in the inner plateau, from 1968 to 2002 (Zhang et al., 2008), and in the Mt. Qomolangma Region of the Himalayas in the last 35 yr (Ye et al., 2009). Using satellite laser altimetry and a global elevation model, Kaab et al. (2012) quantified the glacial thinning in the Hindu Kush-Karakoram-Himalaya region from 2003 to 2008.
Moreover, Gardelle et al. (2012) 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 water level changes 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 Phan et al. (2011) and Zhang et al. (2011), about 150 water level trends of the Tibetan lakes sampled by the ICESat/GLAS LIDAR campaigns between 2003 and 2009 were estimated. The result indicated that most of the lakes have a serious downwards trend in the southern Tibetan plateau and along the Himalaya mountain range, while most of the lakes with a positive water level trend are in the inner plateau during the observing period. Some large lakes on the Tibetan plateau were also monitored by radar altimetry, e.g. Nam Co Lake, as described in Kropacek et al. (2012), Qinghai Lake and Seilin Lake, as reported in (LEGOS, 2012) and by in-situ measurements, e.g. Qinghai Lake in Li et al. (2007) and Nam

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Co Lake in Krause et al. (2010) and Zhang et al. (2011). Moreover, Phan et al. (2012) showed that seasonal variations in lake levels and lake level trends differ considerably for different parts of the Tibetan plateau.

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 et al. (2010) applied the hydrological system model J200g for the Nam Co Lake basin to determine the lake level dependency on temperature, evaporation, precipitation and glacier runoff. The result shows that the simulated lake levels are in good correlation with measurements registered since 2005 and satellite radar altimetry data from 2000 to 2009. In addition, Zhang et al. (2007) 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 Data and methods

In this section, first we introduce the origins and characteristics of all data products used. Conversions in data format or coordinate systems are mentioned as well. Then we define geospatial objects such as a lake catchment, an outlet, a connection between a glacier and a lake, etc. It is also shown how to determine connections between glaciers and lakes. Finally indicators for the dependency of a Tibetan lake on glaciers are defined and computed.

2.1 Data

Main data sources used in this paper include the MODIS land-water mask, the CA-REERI glacier mask, and the HydroSHEDS river 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 connections between lakes and links between glaciers and lakes. To integrate them, all these data are projected onto the WGS84 Geographic Coordinate System.

– The MODIS land-water mask: The water mask, called MODIS MOD44 W 250 m, was produced using a combination of over 8 yr of Terra MODIS spectral data, over 6 yr of Aqua MODIS spectral data and SRTM elevation data (GLCF, 2012). For each 250 m pixel, it is indicated in different ways whether an algorithm decided that the pixel represents water. Except for the lakes, also some parts of rivers are visible. The lakes from the mask are checked with Google Earth and appropriate Landsat TM images. In this way, parts of rivers and empty depressions or holes are removed. Then the lakes over one kilometer square are selected. The downside limit of one kilometer square is a trade-off: a larger limit would decrease the number of lakes in the analysis, while applying a smaller limit would stretch the possibilities of the 250 m MODIS land-water mask too much. This procedure results in 891 lakes over one kilometer square on the Tibetan plateau which occupy a total area of approximately 38 800 km^2, as displayed in Fig. 1.

– The CAREERI glacier mask: The glacier mask is delivered by the World Data Center for Glaciology and Geocryology, Lanzhou (WDC, 2012). This product is distributed in GIS file format as ArcInfo coverage data. It is referenced to the Projected Coordinate System based on the Krasovsky spheroid and the Albers map projection, as detailed in its metadata file. Its attributes consist of the area of each glacier in square meter, perimeter in meter, and glacier identification codes. The

glacier inventory was based on observed data of the glaciers from 1978 to 2002, as reported in Shi et al. (2009). Besides, Shi et al. (2009) also mentioned that a new version of the glacier inventory in a 5 yr project has been started since 2007. The original data was collected and digitized by the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science (CAREERI). The data accuracy is not mentioned in its metadata file. To enable integration with other data, we project the glacier coverage onto the WGS84 Geographic Coordinate System by using a map conversion tool in the ArcGIS Toolbox. In summary, the glacier mask contains 34 676 glaciers, stored as polygons which are representative for the glacier boundaries on the Tibetan plateau. The total area of the glaciers is approximately 53 236 km^2, as also shown in Fig. 1.

– The HydroSHEDS data: The river and drainage basin data is distributed by HydroSHEDS (USGS, 2012). HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) provides hydrographic information in a consistent and comprehensive format for regional and global-scale applications. HydroSHEDS offers a suite of geo-referenced data sets (vector and raster), including stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology information. It is derived from elevation data of the Shuttle Radar Topography Mission (SRTM) at 3 arc-second resolution (a grid cell size of approximately 90 m at the equator). Newly developed algorithms have been applied, including void-filling, filtering, stream burning, and up-scaling techniques while manual corrections were made where necessary as described in Lehner et al. (2006).

The river data, providing surface runoff information, is directly derived from the drainage direction layers. The flow accumulation layer is used for selection and attribution. The river data is built at 15 arc-second resolution (approximately 500 m at the equator). Only rivers with upstream drainage areas exceeding a threshold of 100 upstream cells are selected. The river data is in line vector format where each line is formed by a

from-node (or a starting-point), a list of vertices and a to-node (or an ending point). The river network is referenced to the WGS84 Geographic Coordinate System. Each river reach or segment has a pointer to its corresponding flow accumulation given as a number of grid cells. For example, the inset in Fig. 2 describes the river network in ₅ the Kekexili Lake catchment, and the flow route from Yinma Lake to Kekexili Lake is indicated.

The drainage basin data, describing the catchment areas or the watershed boundaries, is also built at 15 arc-second resolution. This product is formatted as polygon vectors, as shown in Fig. 2. It is also referenced to the WGS84 Geographic Coordinate ₁₀ System. Catchments are attributed with an area in square kilometer, e.g. the Kekexili Lake catchment occupies an area of 2636.5 km^2.

As a matter of fact, there exist discrepancies between notably the CAREERI glacier mask and the other data, for instance the MODIS MOD44W water mask and the HydroSHEDS data. This is illustrated in Fig. 3, where the CAREERI glacier outlines, the ₁₅ MOD44W lakes, the HydroSHEDS river segments and drainage basins are superimposed over a true color image composed from bands 1, 2, and 3 of Landsat-ETM+, collected on 26-08-2002. It is evident that the CAREERI glacier positions are not fully compatible with their position on the Landsat image. In this example, maximum differences are in the average order of approximately 2 km. On the other hand, the MODIS ₂₀ lakes and the HydroSHEDS rivers and catchments match the Landsat image.

2.2 Methods

2.2.1 Determining the catchment of a Tibetan lake

A catchment, also known as drainage basin or watershed, is defined as the area where the surface water from rain and melting snow or ice converges to a single point or ₂₅ outlet, where the water joins another water body such as a lake, river, ocean, etc, as described in (DeBarry, 2004). In a closed catchment, the single point, also called a sink, can be a lake or a point where water is lost underground. As illustrated in Fig. 4,

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all surface runoff in the example catchment converges to Kekexili Lake and the purple boundary describes its closed catchment, i.e. Kekexili Lake is a sink. Each catchment is surrounded by a geographical barrier such as a mountain ridge.

Catchments drain into other catchments in a hierarchical pattern, with smaller catchments, also called sub-catchments, combining to larger catchments. Depending on the application, a sub-catchment can be determined accordingly. In classifying lakes, if there is one river that leaves a certain lake, the lake is not a sink. Therefore the lake catchment is part of a bigger catchment. An example for this case is the Yinma lake, i.e. the Yinma lake catchment is a sub-catchment of the Kekexili lake catchment, as also shown in Fig. 2.

A lake sub-catchment is combined from smaller catchments draining to the lake. As shown in Fig. 4a, each green catchment is representative for an area of at least 100 upstream cells draining to a river segment as determined using the ArcHydro extension of ArcGIS, based on the HydroSHEDS DEM data at 15 arc-second resolution (USGS, 2012). Each river segment drains to an outlet which can also be an origin of a river segment of an adjacent catchment. In this analysis, each river segment stores the number of accumulated upstream grid cells, involving the number of the upstream grid cells of the green catchment itself and the number of accumulated grid cells of river segments from adjacent catchments draining to it. The outlet of the Yinma lake catchment is the point where there exists a river segment leaving the Yinma lake. Subsequently the boundary of the Yinma lake catchment is formed, as shown in Fig. 4b.

2.2.2 Determining connections between glaciers and lakes

Based on the river network, an oriented route of river segments from one node to another can be determined. Accordingly, determining a connection between a glacier and a lake corresponds to finding a route from an origin where the glacier drains into the river network and the outlet of a lake catchment. In most cases, a from-node of a river segment is representative for the origin of the glacier-melt drainage, as illustrated in Fig. 5. A node of the river network is used to be representative for the outlet of a lake

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catchment, as illustrated in Fig. 6. Similarly, a connection between lakes is considered an oriented route from the outlet of a lake catchment to the outlet of another lake catchment. To determine these glacier – lake and lake – lake connections, we build a module in the ArcGIS environment that includes the four procedures below.

5   1. Determining which catchment a glacier belongs to: due to the geographical characteristics of catchment boundaries, each glacier only belongs to one catchment. However, there exist discrepancies between the CAREERI glacier outlines and the HydroSHEDS catchments, as mentioned in Fig. 3. Therefore if a glacier intersects with more than one catchment, it is assumed to belong to that catchment
10   that contains the largest part of the glacier. For example, in Fig. 5 the two glaciers G_1 and G_2 are assumed to belong to catchment Cat_1.

    2. Estimating the origin of the glacier-melt drainage: in reality melt-water from a glacier directly drains to the outlet of one catchment through surface runoff. However, in the glacier mask each glacier is digitized as an undivided polygon, so
15   the melt water from the glacier drains to the outlet, only following one oriented route of river segments. In this study, the source of the route is assumed to be the from-node of a river segment which is nearest to the glacial outline. Thus for each catchment, the distances from a glacier as a polygon, e.g. G_1 to each from-node, e.g. nodes A, B in Fig. 5, are computed, where a distance between
20   a polygon and a point is the minimum distance from the point to a vertex of the polygon. The from-node which has minimum distance to the glacier is the source of the drainage route. A distance threshold from the glacier is used to pre-select potential from-nodes. In Fig. 5, d_{1A} is the minimum distance from a glacier G_1 to potential from-nodes A and B, so the from-node A is assumed to be the origin of
25   the G_1 glacier- melt drainage. Similarly, d_{2B} is the minimum distance of d_{2A}, d_{2B}, and d_{2C}, so from-node B is considered the origin of the G_2 glacier-melt drainage, although in fact the glacier G_2 may also drain its glacier-melt water via from-node

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C. In the other case, d_{3E} is smaller than d_{3D} so from-node E is representative for the origin of the G_3 glacier- melt drainage.

3. Identifying the outlet of a lake catchment: 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. In Fig. 6a and c, point A or point H is the outlet of a closed catchment, therefore point A or point H is a sink. If one river segment leaves the lake and drains to another lake or river, the lake is not a sink. In Fig. 6b and c, point C or point F is the outlet of the sub-catchment of the lake.

4. Indicating the oriented route of river segments from a source down to a destination: 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 Fig. 6. Thus the oriented route from a source as an origin of glacier-melting or an outlet of a lake catchment down to a destination as another outlet can be determined using the following procedure. Firstly the river segment whose from-node coincides with the source belongs to the route. Then if the to-node of the river segment coincides with the from-node of an adjacent river segment, the adjacent river segment is collected to form the route. This process is repeated until the to-node of the river segment coincides with the destination. For example in Fig. 6a, when finding the route from source E to destination A, point D is the point of conjunction, and the route includes two segments ED and DA. Similarly, the route from F to H in Fig. 6c consists of two segments FD and DH.

The module results in shapefiles in GIS polyline vector format where each polyline presents an oriented route from a source to a destination. Its attributes consist of the identification codes of the source and the destination. The module is applied in two cases to determine: (i) a connection from a glacier to a lake: each route with its attributes of the glacial code and the lake code, and (ii) a connection from one lake to another: each route with its attributes of the from-lake code and the to-lake code.

Figure 7 shows the result of the module to determine connections between lakes, and between glaciers and lakes at the Kekexili catchment.

2.2.3 Calculating the area of a lake catchment (A_C)

Based on the HydroSHEDS drainage basin data, it is concluded that most of the catch-
ments inside the inner Tibetan plateau are closed catchments. Lake catchments belong
to the closed catchments or one of the catchments of the major rivers Brahmaputra,
Ganges, Indus, Irrawaddy, Mekong, Salween, Yangtze, or Yellow River. Because the
drainage basin data only distributes shapes and areas of closed-catchments or big
river catchments, in this study, areas of the lake sub-catchments need to be explicitly
calculated as follows.

Computing the area of a lake sub-catchment: fortunately, the HydoSHEDS river data
provides the number of upstream grid cells of each river segment, as illustrated in
Fig. 6. Subsequently the area of each lake catchment can be calculated as the product
of the grid cell size with the total number of the upstream grid cells obtained from all
river segments converging to the outlet of the lake. That is for each sub-catchment the
following steps have to be performed.

1. Obtaining the number of total upstream grid cells: First for each lake an outlet
   should be determined, based on performing the module identifying outlets of lakes
   as mentioned above. Then the total number of the upstream grid cells is the sum
   of the numbers of upstream grid cells directly derived from river segments draining
   to the outlet of the lake. For example in Fig. 6, the total number of upstream grid
   cells flowing into sink A is 1000 cells, into sink H is 500 cells, into outlet C is 850,
   and into outlet F is null. In the case of outlet F, the area of this lake catchment can
   be calculated manually using ArcHydro, as mentioned in the discussion section
   below. In practice, the number of total grid cells representative for the Yinma Lake
   catchment, as illustrated in Fig. 4b, is 3775 grid cells.

2. Calculating the grid cell size in meters: the grid cell size, including width and height, varies regularly depending on its latitude. The grid cell size is approximated using the "haversine" formula (Sinnott, 1984) below:

$$a = \sin^2(\Delta lat/2) + \cos(lat1) * \cos(lat2) * \sin^2(\Delta lon/2)$$
$$c = 2 \cdot a \tan 2(\sqrt{a}, \sqrt{1-a}) \tag{1}$$
$$d = R \cdot c$$

Where d is the shortest distance over the earth's surface – giving an "as-the-crow-flies" distance between the points {(lat1, lon1), (lat2, lon2)}, while Δlat equals (lat2–lat1) as a cell height and Δlon equals (lon2–lon1) as a cell width in radians, and R is earth's radius (mean radius = 6371 km).

Following Sinnott's formula above, the grid cell size depends on the latitudes of the grid cell. The Tibetan lake catchments may actually occupy large areas. The latitude of the outlet of the lake sub-catchment is used to compute the grid cell size, representative for the whole lake sub-catchment. As mentioned in the data section the river data is built at 15 arc-second resolution, the outlet of the Yinma Lake catchment is located at latitude of ∼ 35.62 degree, and therefore the grid cell size is estimated at 0.3766 × 0.6433 km.

According to the information above, the area of the Yinma Lake catchment is approximately 658.7 km^2. Alternatively, the Yinma Lake catchment can also be obtained from its geospatial boundary, as illustrated in Fig. 4b. According to its geospatial boundary, the area of the Yinma Lake catchment is also 658.7 km^2, referenced to the Projected Coordinate System WGS84 UTM.

Obtaining the area of a closed lake catchment: the area of a closed Tibetan lake catchment can be determined by three methods.

1. Directly from the attributes of the HydroSHEDS drainage basin data. For example, the Kekexili Lake catchment is reported to occupy an area of 2636.5 km^2.

2. As the product of the grid cell size with the total number of upstream grid cells. Similar to the computation of the area of the Yinma Lake sub-catchment
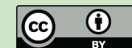
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above, the grid cell size representative for the Kekexili Lake catchment is 0.3767 × 0.6433 km. The total number of grid cells in the Kekexili Lake catchment is 15 100 grid cells. Thus the area of the Kekexili Lake catchment is approximately 2635.3 km^2.

3. Calculated from its geospatial boundary. For example the Kekexili Lake catchment occupies an area of 2636.8 km^2, referenced to the Projected Coordinate System WGS84 UTM.

The small differences in catchment areas are caused by using the representative grid cell size. The bigger the area of the catchment, the larger the difference. Therefore in the following, the area of each Tibetan lake closed-catchment is directly derived from the drainage basin data.

2.2.4 Computing the total area of glaciers draining into a lake

Based on the distribution of the Tibetan glaciers as shown in Fig. 1, it is obvious that part of the glacier melt-water flows downward to some of the Tibetan lakes. A lake can collect glacier-melt water directly from glaciers or indirectly from upstream lakes. Thus for each lake, we distinguish the total area of directly contributing glaciers (A_{GD}) and the total area of upstream glaciers (A_{GU}) draining to it.

$$A_{GD} = \sum_{i=1}^{n} A_i \tag{2}$$

$$A_{GU} = \sum_{i=1}^{n} A_i + \sum_{j=1}^{m} A_{GDj} \tag{3}$$

Where A_i is the area of the i-th glacier directly draining to the lake, and A_{GDj} is the total area of directly contributing glaciers of the j-th upstream lake flowing to the lake.

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Subsequently the total area of glaciers directly draining into Yinma Lake is 41.9 km^2 and into Kekexili Lake is 50.1 km^2, as shown in Fig. 7. Because Yinma Lake is the only upstream lake of Kekexili Lake, the total area of upstream glaciers of Kekexili Lake equals 92 km^2.

2.2.5 Determining the geometric dependency of a lake on glacier runoff

An indicator for the dependency of a lake on glacier runoff is the ratio between the area in the catchment occupied by glaciers and the lake catchment area itself. 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. According to the total area of glaciers draining to the lake, the indicator R_D indicates the geometric dependency of a lake on glaciers directly draining to it while the indicator R_U presents the geometric dependency of a lake on upstream glaciers.

$$R_D = \frac{A_{GD}}{A_C} \tag{4}$$

$$R_U = \frac{A_{GU}}{A_C} \tag{5}$$

Following the results above, the R_D indicator at Yinma Lake equals 0.064, while the R_D indicator for Kekexili Lake equals 0.019. Because there isn't any glaciers-fed lake draining into Yinma Lake, the R_U indicator equals the R_D indicator at Yinma Lake. As Yinma Lake is upstream of Kekexili Lake, the R_U indicator for Kekexili Lake is 0.035.

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3 Results

After defining the geospatial objects and coding the procedures introduced above, the indicators R_D and R_U presenting the dependency of a Tibetan lake on glaciers have been computed for the whole Tibetan plateau. The result shows that 244 Tibetan lakes are directly fed by glaciers while 266 lakes have at least one upstream glacier, possibly buffered by an upstream lake. Moreover, case studies studying the glacial dependency of three lakes are included: the Aksai Chin Lake in the North-Western Kunlun Mountain, the Nam Tso Lake near 100 km north of Lhasa and the 72 km long Yamdrok Lake in the south of Tibet.

3.1 Lake dependency on glaciers for the full Tibetan plateau

3.1.1 Classification of lakes with or without outlet

The Tibetan plateau contains 891 lakes over one square kilometer, occupying a total area of approximate $38\,800\,\text{km}^2$. There are 150 lakes with an area of over $50\,\text{km}^2$. In Table 1 all Tibetan lakes are divided in sinks and lakes with outlet. A lake is considered as a sink if it is the termination point of water flow in a closed catchment. If it is not a sink, a lake has an outlet that drains water into another lake or a river. Apparently, over two third of the Tibetan lake water is contained in sinks. On average, the sink lakes are also four to five times as big as the lakes with outlet. The region defined as the Inner Plateau keeps 86 sinks of a total of 96 sinks having an area of over $50\,\text{km}^2$.

3.1.2 Geometric dependency of Tibetan lakes on direct glacier runoff

Based on the spatial distribution of glaciers and catchments, the glacier area per catchment is computed as shown in Table 2. In this case only the major catchments of the Tibetan plateau are considered. According to Table 2, 25.3 % of the total glacier area directly drains to one of the 244 lakes. These lakes consist of 133 upstream lakes and 111 sinks. 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 $14\,000\,\text{km}^2$ are potential to drain to Brahmaputra River, passing through China, India and Bangladesh. Similarly, most of glaciers of approximate $316\,\text{km}^2$ drain to streams which are origins of Mekong River, supporting fresh water for China, Myanmar, Laos, Thailand, Cambodia and Vietnam.

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 Fig. 8. The result of the grouping the Tibetan lakes by level of the R_D geometric dependency on directly contributing glaciers is also shown in Fig. 9. 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 $2\,\text{km}^2$. They are obviously located near glaciers and spread along mountain ranges in the southern and western Tibetan plateau. Besides, Table 3 shows a list of the top 10 lakes ranked by total area of directly contributing glaciers.

3.1.3 Geometric dependency of Tibetan lakes on upstream glaciers

In addition to being directly fed by glaciers, a Tibetan lake can be fed indirectly by glaciers through other upstream lakes. Accordingly, the 266 R_U indicators are also determined to present the geometric dependency of Tibetan lakes on upstream glaciers. The result of grouping the Tibetan lakes according to their R_U geometric dependency on upstream glaciers is shown in Fig. 9 as well. About 75 % of the lakes with at least one upstream glacier correspond to an R_U indicator of under 0.005. Based on the difference between the total area of directly contributing glaciers A_{GD} and the total area of upstream glaciers A_{GU}, there are 13 lakes with runoff and 9 sinks, which are indirectly fed by glaciers but not directly. Moreover the highest eight R_U indicator values occur for the same lakes having the highest eight R_D indicator values because these lakes are sources of the river network.

3.2 Case studies

Case studies present specific catchments of three lakes Aksai Chin Lake, Nam Tso Lake and Yamdrok Lake. First the Aksai Chin Lake closed catchment contains the small lake with the maximum indicator value R_D for its highest geometric dependency on direct glacial runoff. Geospatial properties of this lake are characteristic for Tibetan lakes having top indicator values R_D. Second the Nam Tso Lake closed catchment is included as it has been a pilot for many studies in lake level change and water balance. Nam Tso Lake mostly depends on directly contributing glaciers on the Nyainqentanglha Mountains. Finally the Yamdrok Lake sub-catchment is surrounded by snow-capped mountains, but Yamdrok Lake highly depends on upstream glacial runoff from surrounding lakes rather than from direct glacial runoff.

3.2.1 Aksai Chin Lake closed catchment

Aksai Chin Lake is a sink on the Aksai Chin plateau. The lake is located at (35.208 N, 79.828 E) in the south of the Kunlun Mountains. Aksai Chin is largely a vast high-altitude desert at an average elevation of 5500 m. In fact, Aksai Chin Lake is fed by Aksai River and many other streams, as illustrated in Fig. 10. The Aksai Chin Lake closed catchment occupies an area of about 8000 km^2, as derived from the HydroSHED drainage basin data. The results indicate that A_{GD} the total area of glaciers directly draining to Aksai Chin Lake equals 673 km^2. As there is only one small lake upstream of Aksai Chin Lake, the total area, A_{GU} of glaciers upstream Aksai Chin Lake is approximately 769 km^2. So the dependency of Aksai Lake on glaciers is determined. Accordingly its R_D value gives $R_D = 0.084$ while its R_U value equals $R_U = 0.096$. We conclude that the dependency of Aksai Chin Lake on glacial runoff is mostly direct, i.e. almost not tempered by intermediate lakes.

The maximum R_D value of 0.816, presenting the dependency of a lake on direct glacier runoff, occurs for a relatively small lake, occupying only 2 km^2. It is located at (35.293 N, 80.572 E) at a height of approximately 5500 m in the Kunlun Mountains, as

shown in Fig. 10. This lake is the only lake draining into Aksai Chin Lake that has glacial runoff. Its sub-catchment occupies an area of about $118 \, km^2$ of which approximately $96 \, km^2$ is covered by glaciers. Thus this lake is almost fully fed by glacial melt water. The geographic properties of this lake are representative for the top eight lakes with an R_D indicator value of over 0.5.

3.2.2 Nam Tso closed catchment

Nam Lake, also called Nam Tso or Nam Co, is the largest salt lake on the Tibetan plateau. The lake is located at (30.718 N, 90.646 E) at an elevation of 4718 m, and occupies a surface area of about $1960 \, km^2$. Nam Tso is a sink at the foot of the Nyainqentanglha Mountains and is mostly fed by glaciers in these mountains. Besides, Nam Tso has two small upstream lakes, but no glacier drains into them. The Nam Tso closed catchment occupies an area of $10741 \, km^2$, as derived from the HydroSHED basin data, while the total area of direct glaciers draining into Nam Tso is calculated as $334.5 \, km^2$. It is one of the top 10 lakes directly fed by glaciers, as shown in Table 2. This high value is reflected by an R_D indicator value of 0.031, which indicates that over 3 % of the Nam Tso catchment is covered by glaciers. Subsequently, this R_D indicator value also confirms the high dependency of Nam Tso on glacial runoff.

According to Krause et al. (2010), the sum of all water inflow to Nam Tso Lake resulted in an increase of the lake volume by $33.5 \, km^3$ for the period between November 1961 and October 2010. Krause et al. (2010) also indicated that the mean total annual inflow of water from glaciers into Nam Tso was computed as $7.12 \, km^3 \, yr^{-1}$ during the observing period, and that this glacial melt water is the largest contributor to the lake water volume. Moreover, based on analysis of satellite laser altimetry data from between 2003 and 2009, Nam Tso has a positive lake level trend of $+23 \, cm \, yr^{-1}$ (Phan et al., 2011), or $+25 \, cm \, yr^{-1}$ (Zhang et al., 2011). In addition, based on analysis of optical data from Hexagon KH-9 and Landsat MSS (both 1976), Metric Camera (1984), and Landsat TM/ETM+ (1991, 2001, 2005, 2009), Bolch et al. (2010) report that the

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glaciers from the Nyainqentanglha Mountains draining into the Nam Tso catchment shrink during the period 2001–2009.

It should be noted that Nam Tso is an exception among the many lakes on the Tibetan plateau, in the sense that it is relatively well studied. In our opinion the results for Nam Tso indicate the potential of the approach of this paper. Indeed, the geometric dependency of Nam Tso on glacial runoff is encoded by our R_D indicator, while results from other papers indicate a link between glacial shrinkage and lake level increase. The possible significance of these links should be studied further for a large number of lakes however.

3.2.3 Yamdrok Lake sub-catchment

Yamdrok Lake, also called Yamzho Yumco, is one of the largest lakes on the Tibetan plateau. The lake is fan-shaped and occupies an area of about $640 \, \text{km}^2$. It is located at (28.979 N, 90.717 E) at an elevation of about 4440 m on the north side of Mount Everest/Qomolangma. The lake is fed by numerous small streams. The outlet stream of the Yamdrok Lake sub-catchment is at the far western end of the lake, as shown in Fig. 12. The Yamdrok Lake sub-catchment occupies an area of $9940 \, \text{km}^2$, as derived from the HydoSHED drainage basin data and belongs to the major catchment of Brahmaputra River. Although surrounded by many snow-capped mountains, the glaciers that directly feed Yamdrok Lake occupy only $21 \, \text{km}^2$. Thus the R_D indicator, the geometric dependency of Yamdrok Lake on direct glacial runoff, only equals 0.002. However, the total area of glaciers upstream of Yamdrok Lake is $255 \, \text{km}^2$. Subsequently the dependency of Yamdrok Lake on upstream glaciers is relatively high, R_U 0.026. It means that Yamdrok Lake depends on runoff from upstream lakes more than on direct glacial runoff.

The results also indicate that three close by lakes Bagyu, Gongmo and Phuma flow into Yamdrok Lake, as shown in Fig. 12. Although no glacier directly feeds it, Bagyu Lake depends on glacial runoff passing first through a nearby small lake with the R_D indicator value of 0.004. That is, Bagyu Lake has the R_U indicator value of 0.004.

Yamdrok Lake has a high dependency on glacial runoff from Gongma Lake and Phuma Lake.

Gongmo Lake is one of the lakes upstream of Yamdrok Lake. The lake occupies an area of about $40\,\text{km}^2$. It is located at a height of $4500\,\text{m}$ near the western end of Yamdrok Lake. The Gongmo Lake sub-catchment occupies an area of $620\,\text{km}^2$ while $77.7\,\text{km}^2$ of the sub-catchment area is covered by glaciers. Therefore the dependency of Gongmo Lake on direct glaciers is high, with the R_D value equaling 0.125.

Phuma Lake, also called Puma Yumco, is a big upstream lake draining to Yamdrok Lake, as shown in Fig. 12. Phuma Lake occupies an area of about $285\,\text{km}^2$ and is located at a height of $5030\,\text{m}$. The lake is directly fed by melt water from surrounding mountains. The area of the Phuma Lake sub-catchment equals around $1815\,\text{km}^2$. The result indicates that the total area of directly contributing glaciers draining to Phuma Lake is about $153\,\text{km}^2$. Therefore Phuma Lake also highly depends on direct glacial runoff.

4 Discussion

4.1 Calculating the area of a lake sub-catchment using ArcHydro manually

In Sect. 2.2.3, the area of a lake sub-catchment is computed as the product of the grid cell size with the total number of accumulated grid cells draining into the representative outlet of the sub-catchment. Due to the limited resolution of the HydroSHED river network, however, the outlet of a lake sub-catchment can be just one of several sources of a river network, e.g. outlet F in Fig. 6c. In this particular case, the total number of accumulated grid cells cannot be determined automatically from the HydroSHEDS data. Nevertheless, the area of a lake sub-catchment can also be calculated based on its geometric shape. The ArcHydro extension of ArcGIS supports the manual outlining of catchments from a digital elevation model.

Based on the HydroSHED DEM data at 15 arc-second resolution, the geometric shape of lake sub-catchments in the case the total number of upstream grid cells draining into the lake cannot be determined automatically are created manually using the ArcHydro tools. In practice, there exist 19 such lakes directly fed by glaciers. Firstly the terrain data for the 19 lake regions are clipped from the HydroSHED DEM. Secondly the small catchments are created in steps following the ArcHydro user guide. For this purpose, a threshold of 30 upstream drainage grid cells is used to define a river segment, to improve the level of detail of the river network. It also means that small catchments with an area of at least 30 grid cells will be built. Finally for each lake the lake sub-catchment is merged from the small catchments draining into its outlet, as illustrated in Fig. 4. Subsequently, its area can be obtained directly from its geometric shape. For example, the geometric shapes of the three small lake sub-catchments in the south of the Palku Lake closed catchment are determined as shown in Fig. 13.

4.2 Dividing the Tibetan plateau into smaller parts for speeding up the computations

The Tibetan plateau is a large region, so it takes so long time to perform the drainage network analysis module, determining connections between glaciers and lakes. For example when the module was run on a desktop with CPU 3.2 GHz and 2 GB RAM or on a laptop with Core 2 Duo CPU 2.2 GHz and 4 GB RAM, it took 4 or 5 days to process the data for the whole Tibetan plateau. Sometimes the processing got stack. Although the river network is organized per catchment, a large amount of PC memory is requested to find a route of river segments for each glacier. Especially, the major catchment of Brahmaputra River occupies a large area, and the river network spreads out densely. Besides, most of the glaciers inside the Brahmaputra major catchment don't drain into the outlet of any lake catchment. Thus to calculate the total area of directly distributing glaciers draining into each lake on the whole plateau, we divided the plateau into sub-areas, grouping some closed catchments in the inner plateau. It means that the module to determine connections between glaciers and lakes has been

run for several times manually. Moreover, for each major river catchment we created several virtual outlets in the river network to reduce the time of the performing the network analysis. Then the module to make connections between the virtual outlets, similar to make connections between lakes, has been applied. Finally, the connections between glaciers and lakes in each major catchment are found by combining routes from glaciers to outlets and between outlets.

5 Conclusions

In this paper, the geometric dependency of each lake on glacial runoff is calculated 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. Based on drainage network analysis, geometric connections between glaciers and lakes are determined. Then the total area of directly contributing glaciers or the total area of upstream glaciers draining into a lake is computed. This geometric dependency is just a proxy for the actual dependency of a lake on glacial runoff. Still, our results clearly list which lakes are more or less dependent on glacial runoff and therefore indicate which lakes are expected to be strongly affected by the predicted further shrinkage of the glaciers on the Tibetan plateau.

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Table 1. Tibetan lakes with and without outlet.

No.	Catchment	Upstream lakes	Total area of upstream lakes (km^2)	Sinks	Total area of sinks (km^2)
1	Brahmaputra	78	1535.3	3	53.6
2	Ganges	14	78.5	2	330.1
3	Indus	28	1333.5	5	212.7
4	Irrawaddy	0	0	0	0
5	Mekong	3	15.3	1	17.7
6	Salween	16	253.4	0	0
7	Yangtze	87	965.4	13	1157.9
8	Yellow River	56	2165.6	2	4170.1
9	Inner plateau	323	5949.0	260	20560.7
	Total	605	12296.0	286	26502.8

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Table 2. Glacier area per catchment 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.	Catchment name	Catchment 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	1748.2	11.1
2	Ganges	39 772	3 636	10	355.5	9.8
3	Indus	101 428	2430	14	727.9	30.0
4	Irrawaddy	4227	32	0	0.0	0.0
5	Mekong	86 392	327	2	11.0	3.4
6	Salween	108 266	1893	4	53.4	2.8
7	Yangtze	484 317	2432	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	9909.7	37.4
	Total	2 531 240	53 236	244	13 492.8	25.3

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Table 3. Top 10 lakes ordered by total area of directly contributing glaciers. A_C is the area of the lake catchment, A_{GD} is the total area of glaciers directly draining into the lake, and R_D is the geometric dependency of the lake on direct glacial runoff.

No.	Lake name	Latitude	Longitude	Lake area (Km^2)	A_C (Km^2)	A_{GD} (Km^2)	R_D
1	Dongtaiji'nai'er Lake	37.496	93.935	223	34 148	691.5	0.020
2	Aksai Chin Kul	35.208	79.828	166	7993	672.8	0.084
3	Ligmen Tso	35.028	81.082	249	2727	518.7	0.190
4	Ngagong Tso	29.413	96.817	9	1290	484.6	0.376
5	Ayakum Kul	37.546	89.373	631	24 147	383.7	0.016
6	Nam Tso	30.718	90.646	1967	10 741	334.5	0.031
7	Draksum Tso	30.026	93.997	26	1722	307.2	0.178
8	Nganglaring Tso	31.540	83.101	500	12 464	291.2	0.023
9	Achik Kul	37.067	88.431	355	13 263	280.8	0.021
10	Dabsan Nor	36.978	95.205	294	109 629	242.7	0.002
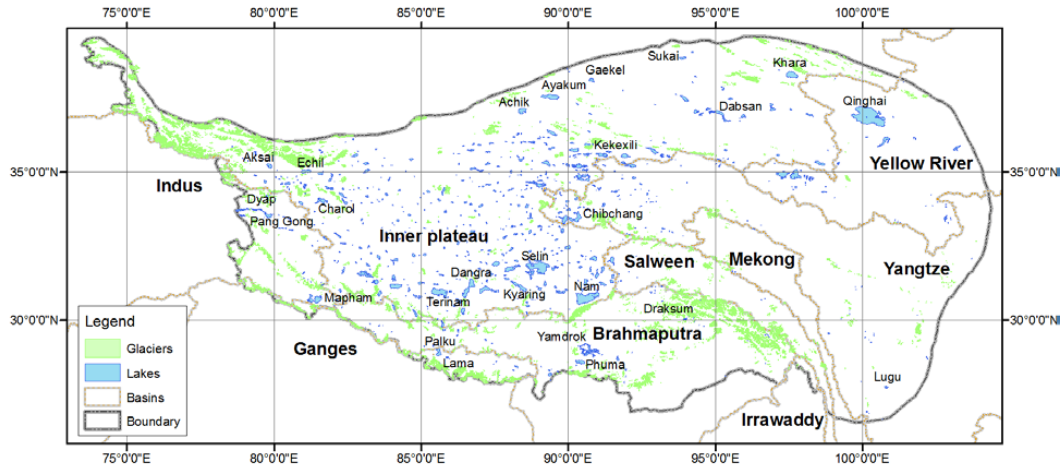
Fig. 1. Glaciers and lakes on the Tibetan plateau.
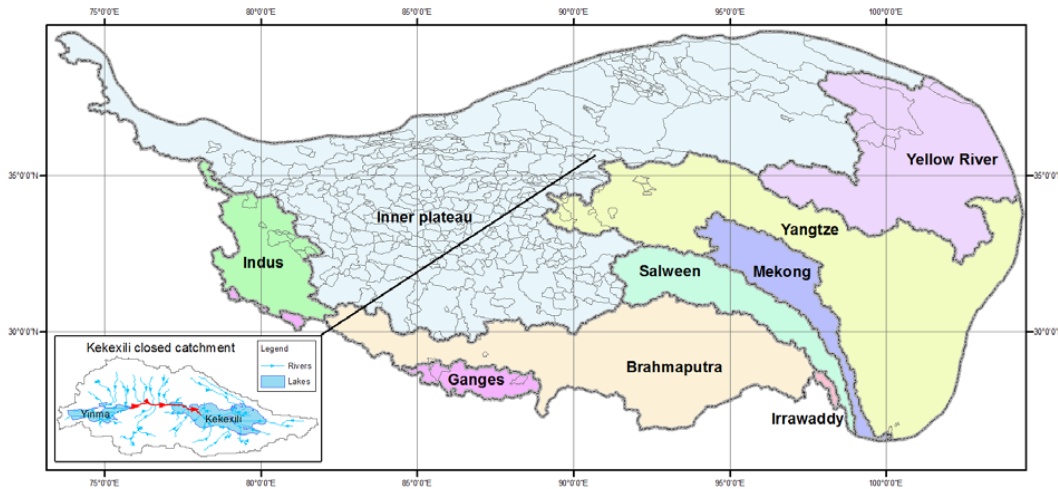
Fig. 2. Tibetan catchments derived from HydroSHEDS and the river network at the Kekexili catchment.
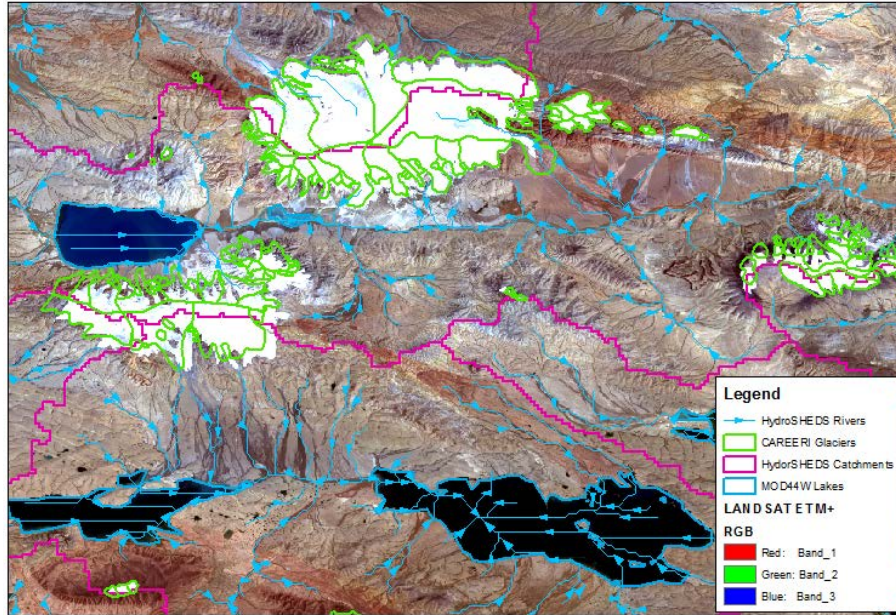
Fig. 3. CAREERI glacier mask data, MODIS MOD44W land-water mask data and HydroSHEDS rivers and basin outlines superimposed over Landsat-ETM+. Notably a discrepancy between the CAREERI glacier outlines and the location of the glaciers on the Landsat image can be observed.
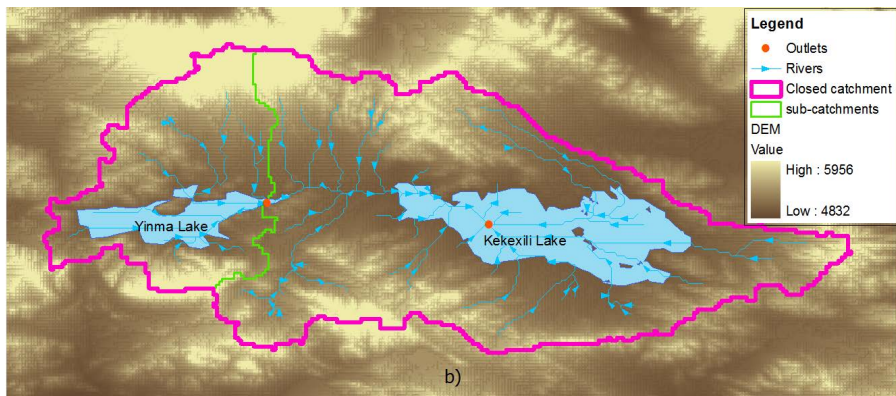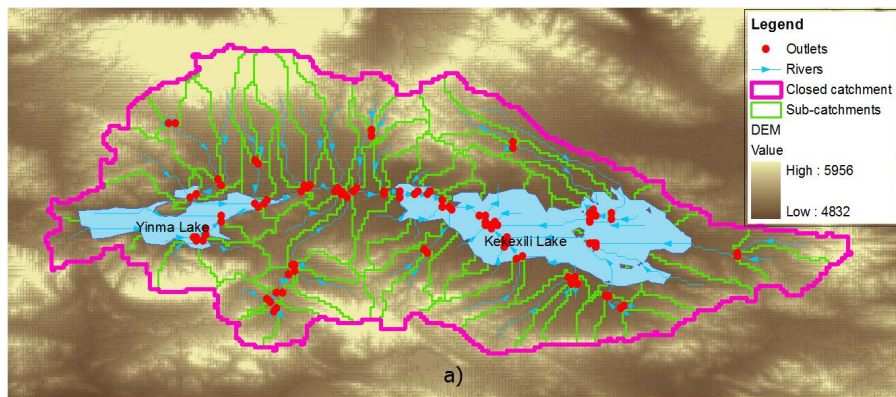
Fig. 4. (a) Catchments representative for an area of at least 100 upstream cells draining to a river segment based on the HydroSHEDS DEM data at 15 arc-second resolution, and **(b)** the Yinma Lake sub-catchment as part of the Kekexili Lake closed catchment.
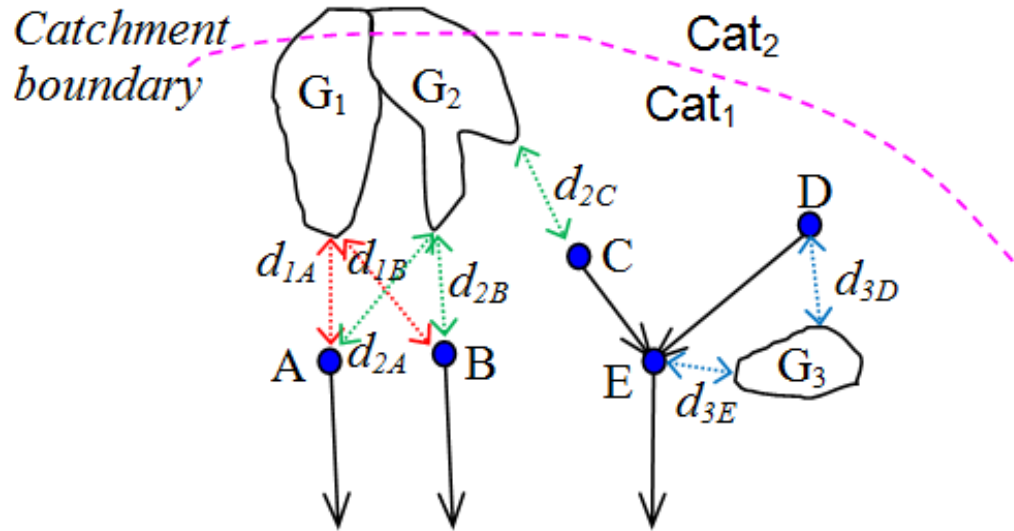
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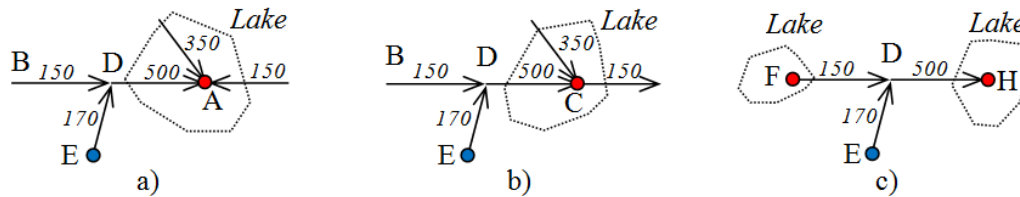
Fig. 6. The sink A or H of a closed catchment and the outlet C or F of a sub-catchment.
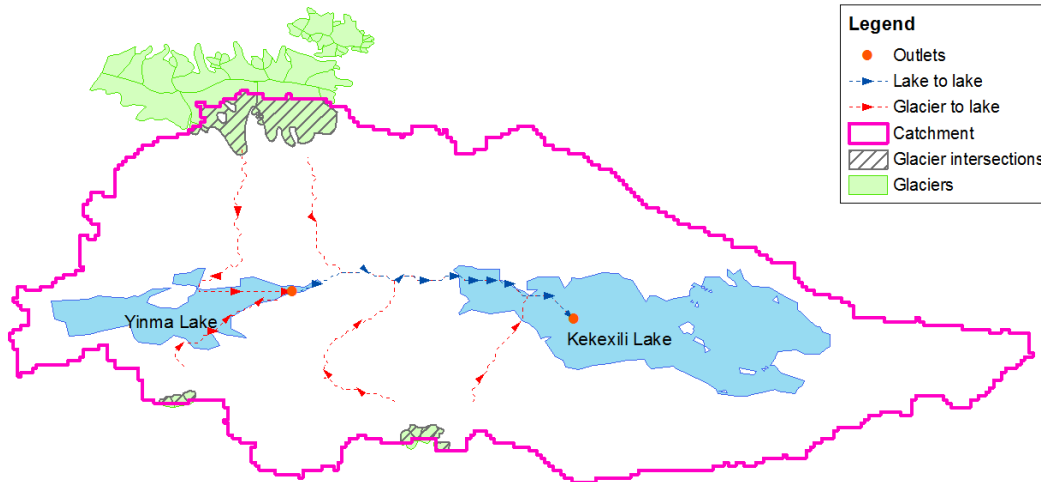
Fig. 7. Determining the glaciers inside the Kekexili catchment, the connections from glaciers to Yinma Lake and Kekexili Lake, and the route from Yinma Lake to Kekexili Lake.

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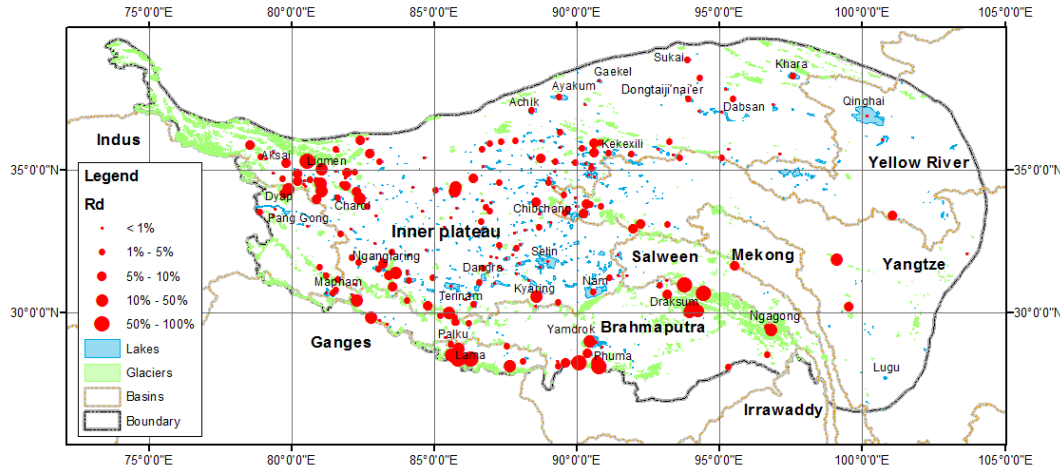
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Fig. 9. Grouping Tibetan lakes by level (%) of their geometric dependencies R_D and R_U on glacial runoff.
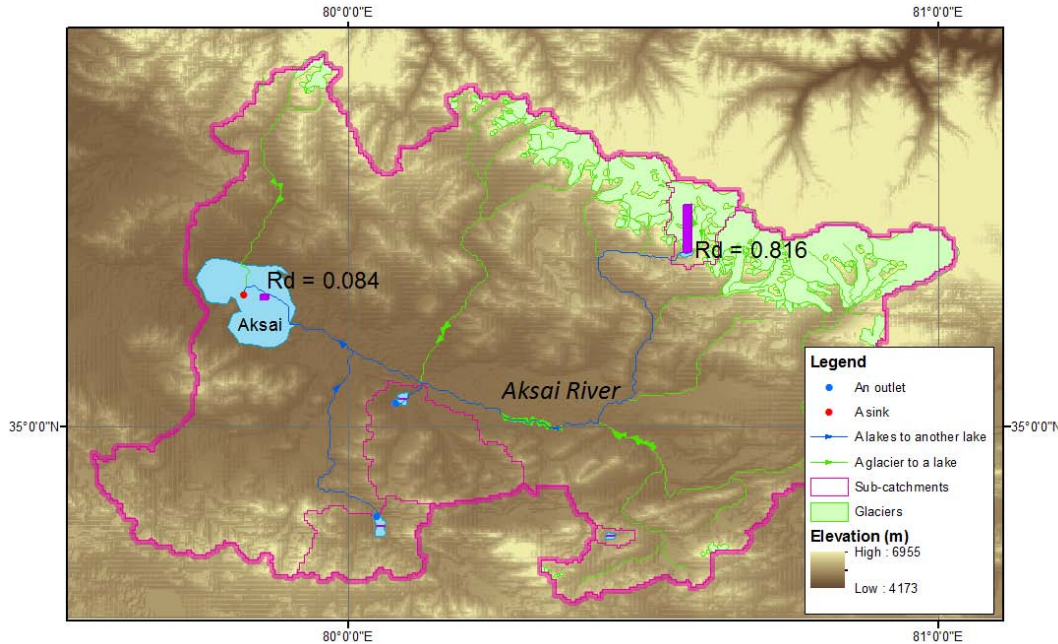
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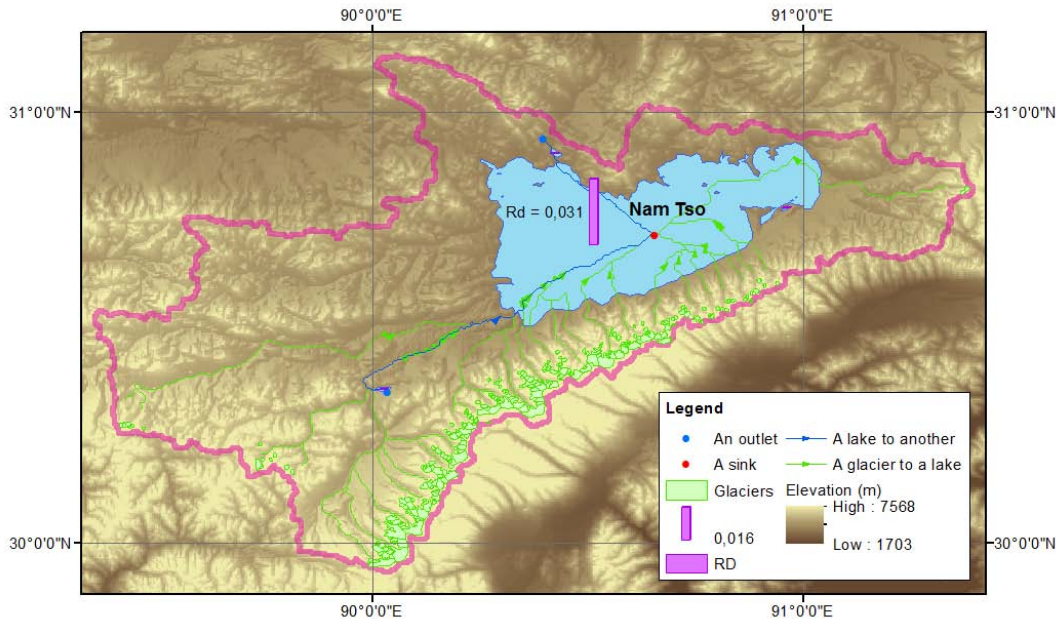
Fig. 11. High dependency of Nam Tso on glacial runoff.
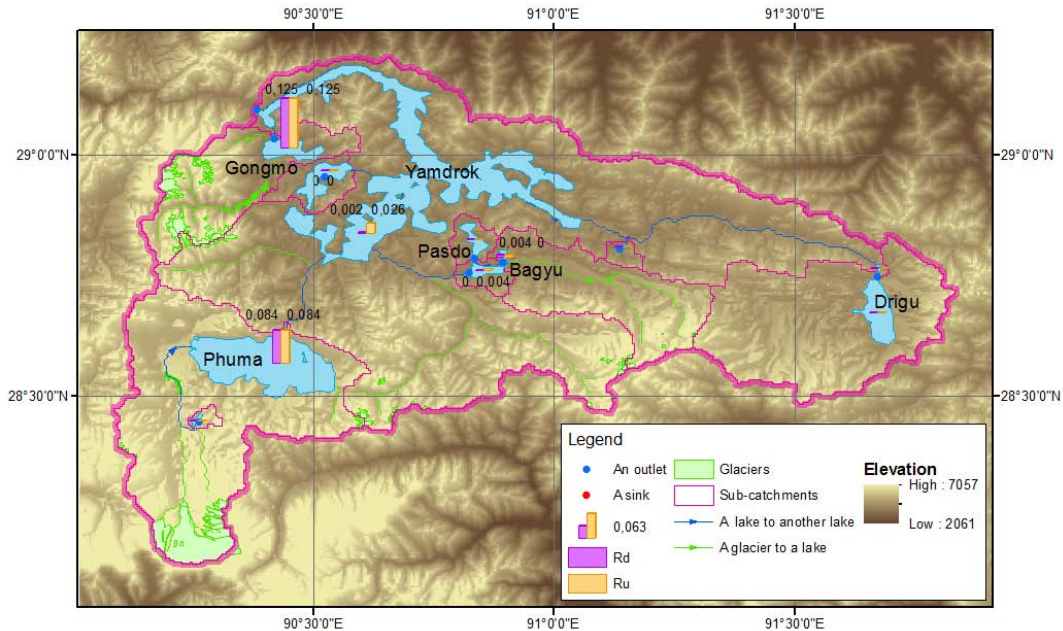
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Fig. 13. Computing the area of a lake sub-catchment using ArcHydro manually.