Dr. Simon Cook
School of Science and the Environment
Manchester Metropolitan University
Chester Street
Manchester
M1 5GD
UK

23 November 2015

Revised manuscript for *Earth Surface Dynamics* esurf-2015-34-R1

Dear Dr. Turowski,

I am hereby submitting a revised version of our manuscript for *Earth Surface Dynamics* (esurf-2015-34-R1) entitled "*Estimating the volume of Alpine glacial lakes*". This document includes the following sections:

- Cover letter (current page)
- Interactive comment – Reply to W. Haeberli (ESurfD-3-C342-2015)
- Interactive comment – Reply to Anonymous Reviewer 1 (ESurfD-3-C344-2015)
- Interactive comment – Reply to Reviewer 2, J. Herget (ESurfD-3-C346-2015)
- Revised manuscript with mark-up and comments about changes made in response to reviewer comments.

Most comments from the reviewers were minor in nature and have been edited very easily. Perhaps the most substantial suggested change came from Reviewer 2 asking us to consider the inclusion of data from two Russian reports. Thank you for granting us an extension to look into this possibility. On the same day as you granting us an extension, the Russian contact (Prof. Konovalov) suggested by Reviewer 2 got in contact with us, copying in some tables of data from the Russian literature. In the end, we did not include these additional data for several reasons outlined in our response to the reviewer below. Frankly, we could not be sure of the nature of the data (whether they were measured or derived empirically), nor of the types of lake that were studied (or even if they were ice-contact lakes as examined in our study).

We hope that the revised manuscript is acceptable for publication in *Earth Surface Dynamics*. If you have any further suggestions or queries then please do not hesitate to contact us.

Yours sincerely,

Simon Cook
Senior Lecturer in Physical Geography
S.J.Cook@mmu.ac.uk
0044 161 2471202

Interactive comment – Reply to W. Haeberli (ESurfD-3-C342-2015)

S.J. Cook and D.J. Quincey

S.J.Cook@mmu.ac.uk and D.J.Quincey@leeds.ac.uk

We thank Wilfried Haeberli for his positive contribution to discussion on the issue of volume estimation for Alpine glacial lakes (comment ESurfD-3-C342-2015). It is encouraging to see that our work is welcomed as a valuable contribution. Two key points emerge from this comment, which we discuss further here.

Firstly, we refer several times in our manuscript to “measured” lake volumes. As outlined in the interactive comment, these lake volumes are not truly measured, but instead represent calculated volumes derived from interpolated bathymetric data. Hence, in any revised version of our manuscript it would be necessary to avoid the use of the term “measured” when referring to lake volumes that have been calculated in this way.

Secondly, the comment raises the issue of auto-correlation between lake area and volume (area multiplied by mean depth). We have mentioned this issue on p914, as stated in the comment, and also on p919. It is suggested in the comment that we reflect further on this issue. Essentially, we agree with this perspective – plotting lake area against volume gives an unrealistic impression of the predictability of volume from measured area, often accompanied with high r^2 values. The level of unpredictability is demonstrated in Fig 1 and Table 1, which illustrates a wide range of lake depths for any given area. In our manuscript, we have been conservative in our discussion of V-A auto-correlation – we sought to present the data in the same way as in previous studies, and to mention the issue of auto-correlation, but we did not critique this approach in any detail. We agree that in any revised version of the manuscript that it would be important to highlight more fully the shortcomings of presenting and employing somewhat misleading volume-area relationships.

Interactive comment – Reply to Anonymous Reviewer 1 (ESurfD-3-C344-2015)

S.J. Cook and D.J. Quincey

S.J.Cook@mmu.ac.uk and D.J.Quincey@leeds.ac.uk

We thank Reviewer 1 for their review of our work. Most of the questions asked of the reviewer have been answered with the response "Yes", with no further action required. Questions 5, 13, 14, and 15 all require responses. Responses to reviewers are requested in the following format: (1) comments from Referees, (2) author's response, (3) author's changes in manuscript. We follow this structure for each of the questions outlined above.

Q5:

(1) The reviewer asks us to clarify our statement in section 4.3 regarding our critique of empirical relationships that are based on regional datasets. The reviewer notes the case of Himalayan glacial lakes that do appear to exhibit a regional trend. The reviewer asks us how we identified outliers in the dataset in section 3.1.

(2) The reviewer refers to p922 line 28 where we suggest that relationships used to estimate lake volumes based on collating information by region should not necessarily be expected to perform any better at predicting lake volume than relationships that are derived from a wide range of sites and regions. We use as evidence for this the example of lakes in the Southern Alps of New Zealand, which are in close proximity to one another, yet have different levels of volume predictability (under- and over-predicted) - our point being that lakes in this region must be unusually deep or shallow for their respective areas. Hence, it is unlikely that any regional trend exists here. The reviewer remarks that (1) we have made this statement without actually running the analysis by region, and (2) that the consistent under-prediction of Himalayan glacial lake volumes indicates that a regional relationship may perform better there. These are fair comments, and ultimately we have clarified our point in the revised manuscript taking into consideration these issues.

Taking the example of New Zealand (although also applicable to other regions), there are relatively few data points to test whether or not a regional relationship could out-perform existing empirical relationships (such as that of Huggel et al., 2002). Hence, we have made a suggestion that can be treated as a hypothesis to be tested in future work, i.e. that regional relationships will not necessarily out-perform existing empirical relationships. The case of New Zealand supports that point, but the case for the Himalaya indicates that there may be some merit in regional relationships, as highlighted by Reviewer 1. However, our key point remains: any relationship (general, regional, context-based or otherwise) should be applied judiciously. In reality, we suspect that there are regional controls on erosion, sediment transfer and deposition that ultimately lead to the development of lakes with potentially predictable characteristics. However, even within regions there can be significant differences in glacier character that lead to significant differences in lake depth, and hence volume. We believe that the point we are making needs to be made in order to stimulate further work on this issue. We have clarified and elaborated on our point, incorporating the sensible comments of Reviewer 1.

Reviewer 1 also comments that we need to discuss how outliers have been identified (as alluded to on p916 Line 7). Frankly, in making this statement we have simply made a visual assessment – looking at Fig 1 there's a lot of scatter about the best fit line and the line representing Huggel et al.'s (2002) relationship. We have clarified this point, and have also removed reference to "significantly" because we did not undertake a statistical significance analysis here – we have replaced this with "greatly" and now refer specifically to the fact that outliers were determined visually from Fig. 1. A full error analysis is presented later in Table 3.

(3) We have clarified our point about the performance of regional relationships in section 4.3. We have clarified our assessment of outliers in section 3.1.

Q13:

(1) Reviewer 1 recommends harmonising lowercase lettering in figure 3 and caption.
(2) Agreed.
(3) We have changed all letters in the figure to lowercase.

Q14:

(1) The reviewer notes some missing references, reference edits, and asks us to check all references.
(2) Agreed.
(3) We have added the missing reference by Richardson & Reynolds (2000) to the reference list, checked the inclusion of other cited references, and changed the Mool et al. references to ICIMOD. In doing this, we removed the reference to Haeberli (1983), which was not cited in the text.

Q15:

(1) The reviewer recommends adding a "lake type" column to the Supplementary data table.
(2) Good point.
(3) We have done this in the Supplementary Tables 1 and 2.

Interactive comment – Reply to Reviewer 2, J. Herget (ESurfD-3-C346-2015)

S.J. Cook and D.J. Quincey

S.J.Cook@mmu.ac.uk and D.J.Quincey@leeds.ac.uk

Firstly, we thank the reviewer for his thorough consideration of our manuscript, and we are pleased that he sees value in our contribution. The reviewer appears to be in broad agreement with our primary arguments. The reviewer focuses his critique of our work around 3 themes. We deal with these points here in turn. Responses to reviewers are requested in the following format: (1) comments from Referees, (2) author's response, (3) author's changes in manuscript. We follow this structure for each of the questions outlined above.

Issue 1

(1) The reviewer recommends that we consider adding further data from two Russian reports to enrich the dataset presented and analysed in the manuscript.

(2) The reviewer makes a valuable point that previous publications have tended to ignore potentially useful datasets if the source of the information is written in a language that differs from that of the author(s). Specifically, it is recommended that we consider adding lake measurement information published in Glazirin et al (2013), and from two Russian reports by Nikitin (1987) and Tsarev (2003). We would like to acknowledge the reviewer here, because he provided us kindly with hard and electronic copies of Glazirin et al., which is greatly appreciated.

Inclusion of the lake information published in Glazirin et al. (2013) would be problematic. Firstly, one key element of data that we require for part of our analysis (such as in Fig1 and Table 1) is lake depth, which is not presented in Glazirin et al. (2013). Secondly, the lake area information in Glazirin et al. (2013) is approximated by the area of an ellipse, where lake length and width are the input data. We have avoided area approximations of this sort in our compiled dataset. Thirdly, the relationship between lake area and volume presented in Glazirin et al. suffers from the same issue of auto-correlation that we have referred to on p914 and 919 in our manuscript, and which has been commented on in an exchange between ourselves and another reviewer (see comments ESurfD 3, C342–C343, 2015 and ESurfD 3, C368–C369, 2015). Hence, we cannot use these calculated volumes in our dataset. Taken together, these issues do not permit the inclusion of the dataset presented in Glazirin et al. (2013).

As the reviewer notes, the volume-area relationship published in Glazirin et al. (2013) is derived from two reports by Nikitin (1987) and Tsarev (2003), and the reviewer directed us to a Russian colleague (Prof. Vladimir Konovalov) who could have access to these original reports. We contacted Prof. Konovalov soon after receiving the review and he provided a paper (in Russian) that he thought might help us [Konovalov, VG (2009) Remote sensing monitoring of the outburst hazardous lakes in Pamir. *Криосфера Земли*, т. XIII, № 4, с. 80–89]. Again, however, the data presented within are of limited use for our manuscript – Fig 1 of the paper indicates that depths have been calculated rather than measured; depths represent maximum rather than mean values; and lake volumes are calculated using empirical formulae.

Prof. Konovalov kindly sent tables of data from the reports by Nikitin (1987) and Tsarev (2003). Some of these tables provide details of lake area and volume only, and some provide other morphometric information, which we interpret to be depth, moraine height, lake length, etc. We are reluctant to include these data in our compiled dataset because it is unclear to us (1) where these lakes are located; (2) what type of lake or context each datapoint represents; (3) whether the area, depth and volume measurements are estimated (as described above for Glazirin et al.) or measured in some way. For example, it is unclear whether these lakes are ice-contact (moraine-, ice-dammed or supraglacial) lakes, as required for our study, or whether they are lakes that have been abandoned by the glacier (i.e. any lake in an Alpine environment). The latter is not under consideration in our manuscript.

(3) Given these uncertainties about the nature of the lake data presented in these studies, we regret that we are unable to include them in our study. We certainly see value in these other contributions and hope that this discussion has highlighted their existence to a broader audience.

Issue 2

(1) The reviewer comments that our selection of the most recent lake data to present in Table 1 and 2 is a poor argument as it hides the variability in the dataset.

(2) Firstly, it is worth re-iterating that relationships derived from any duplicate measurements are already presented in Tables 1 and 2 and Figures 1 and 2. We also state on p914 line 4, line 14 and the caption for Fig1, that duplicate measurements have been presented. We present the additional relationships in Tables 1 and 2 where duplicate measurements from the same lake are removed with only the most recent measurements presented. Our logic for this is simple: the most recent measurements provide the most relevant and up-to-date information on any one lake. It would not be pragmatic to present all combinations of lake data for different duplicate measurements. Interested readers could derive their own graphs and relationships from the Supplementary Dataset if this were of interest to them.

(3) In the revised manuscript we have taken the advice of the reviewer and made the point that lake areas and volumes can vary seasonally or daily depending on a range of factors. This is now presented in section 2, Data and Methods.

Issue 3

(1) The reviewer requests that we add a value for range in lake area to Tables 1 and 2.
(2) Agreed.
(3) We have now added ranges in depth and area to Table 1, and ranges in area and volume to Table 2.

Estimating the volume of Alpine glacial lakes

S. J. Cook^1, D. J. Quincey^2

[1] School of Science and the Environment, Manchester Metropolitan University, Chester Street, Manchester, M1 5GD, UK

[2] School of Geography, University of Leeds, Leeds, LS2 9JT, UK

Correspondence to: S.J.Cook@mmu.ac.uk (+44 [0]161 247 1202) and D.J.Quincey@leeds.ac.uk (+44 [0]113 343 3312)

Abstract

Supraglacial, moraine-dammed and ice-dammed lakes represent a potential glacial lake outburst flood (GLOF) threat to downstream communities in many mountain regions. This has motivated the development of empirical relationships to predict lake volume given a measurement of lake surface area obtained from satellite imagery. Such relationships are based on the notion that lake depth, area and volume scale predictably. We critically evaluate the performance of these existing empirical relationships by examining a global database of ~~measured~~ glacial lake depths, areas and volumes. Results show that lake area and depth are not always well correlated ($r^2 = 0.38$), and that although lake volume and area are well correlated ($r^2 = 0.91$), and indeed are auto-correlated, there are distinct outliers in the dataset. These outliers represent situations where it may not be appropriate to apply existing empirical relationships to predict lake volume, and include growing supraglacial lakes, glaciers that recede into basins with complex overdeepened morphologies or that have been deepened by intense erosion, and lakes formed where glaciers advance across and block a main trunk valley. We use the compiled dataset to develop a conceptual model of how the volumes of supraglacial ponds and lakes, moraine-dammed lakes and ice-dammed lakes should be expected to evolve with increasing area. Although a large amount of bathymetric data exist for moraine-dammed and ice-dammed lakes, we suggest that further measurements of growing supraglacial ponds and lakes are needed to better understand their development.

Commented [SC1]: Here, and throughout the manuscript, we have removed reference to measured volumes in response to the interactive comment by Prof. Haeberli.

Commented [SC2]: We have highlighted the auto-correlation issue here as outlined in the interactive comment by Prof. Haeberli.

1 Introduction

Globally, there is a general trend of mountain glacier recession and thinning in response to climatically controlled negative mass balances (Zemp et al., 2015). In most mountain ranges, glacier shrinkage since the Little Ice Age has been accompanied by the development of proglacial, ice-marginal and supraglacial lakes impounded by moraine and outwash fan head structures (e.g. Röhl, 2008; Janský et al., 2009; Thompson et al., 2012; Carrivick and Tweed, 2013; Westoby et al., 2014). The integrity of these structures often reduces over time as ice cores degrade and slopes are subject to mass wasting processes, raising the concern of dam failure. Further, the location of these lakes in valleys with steep, unstable slopes, often in tectonically active regions prone to earthquakes, means that rock and ice avalanches are common, adding a further threat of displacement-wave overtopping if avalanche material were to impact the lake (e.g. Schneider et al., 2014). Dam failure, breach or overtopping can lead to glacial lake outburst floods (GLOFs) that pose a significant threat to lives, industry and infrastructure (Richardson and Reynolds, 2000; Westoby et al., 2014). Other potentially dangerous lakes are dammed by ice, either in ice-marginal locations where surface meltwater or water from tributary valleys ponds against the glacier margin (e.g. Merzbacher Lake - Mayer et al., 2008; Lac de Rochemelon - Vincent et al., 2010), or where advancing (often surging) glaciers block river drainage (e.g. Kyagar Glacier - Haemmig et al., 2014). In these situations, water may escape through subglacial tunnels, or along the ice margin between the glacier and valley side, or by mechanical failure of the ice dam (Walder and Costa, 1996; Clague and Evans, 2000).

Crucial to the management of GLOF hazards is the ability to assess the likelihood and magnitude of any such event. In most cases, this requires an understanding of the volume of water impounded in the lake, the structural integrity and longevity of the dam, potential external trigger mechanisms, and the likely flow path of the flood (e.g. Richardson and Reynolds, 2000; McKillop and Clague, 2007; Westoby et al., 2014). There are a number of challenges for anyone interested in ~~measuring~~ estimating or ~~estimating~~ calculating lake volume. Field studies are complicated by the fact that many glacial lakes are located in relatively inaccessible or physically challenging and dangerous environments, making bathymetric surveys of lake basins difficult. As yet, there is no reliable technique available for measuring lake bathymetry or volume from satellite imagery where turbidity precludes the derivation of reflectance-depth relationships (e.g. Box and Ski, 2007). Consequently, a number of studies have adopted an empirical approach to volume calculation from satellite imagery

Commented [SC3]: As in the abstract, we have changed the language throughout pertaining to measured vs. estimated lake volumes according to the interactive comment by Prof. Haeberli.

based on known relationships between ~~measured~~ lake depths, areas and volumes (e.g. Evans, 1986; O'Connor et al., 2001; Huggel et al., 2002; Yao et al., 2012; Loriaux and Cassassa, 2013; Carrivick and Quincey, 2014). This allows rapid and simple calculation of lake volumes from widely available satellite imagery, whilst avoiding the necessity for often challenging fieldwork.

Two key empirical approaches have become adopted for lake volume estimation. First, O'Connor et al. (2001) derived a relationship between lake area and volume for moraine-dammed lakes of the Central Oregon Cascade Range. Lake volumes were derived from detailed bathymetric surveys. The relationship takes the form:

$$V = 3.114\,A + 0.0001685\,A^2. \tag{1}$$

Where V is lake volume (in m^3) and A is the surface area of the lake (in m^2). This relationship has been applied, for example, to assist in the prediction of GLOF hazards in British Columbia by McKillop and Clague (2007).

An alternative relationship was derived by Huggel et al. (2002). First, Huggel et al. demonstrated that lake depth and area were correlated for a combination of ice-dammed, moraine-dammed and thermokarst lakes at a number of locations globally. This relationship takes the form:

$$D = 0.104\ A^{0.42}. \tag{2}$$

Where D is the mean lake depth (in metres), and area is measured in m^2. Hence, Huggel et al. (2002) derived a relationship for volume (in m^3) with the form:

$$V = 0.104\ A^{1.42}. \tag{3}$$

As the authors point out, this relationship has much in common with that of the Canadian Inland Water Directorate, cited in Evans (1986), which is based on ice-dammed lakes and takes the form:

$$V = 0.035\ A^{1.5}. \tag{4}$$

The relationship of Huggel et al. (2002) has gained significant appeal and has been applied directly in several studies to estimate lake volume (e.g. Huggel et al., 2004; Bolch et al., 2011; Mergili and Schneider, 2011; Jain et al., 2012; Gruber and Mergili, 2013; Wilcox et al., 2013; Byers et al., 2013; Che et al., 2014), or has been modified for specific locations (e.g. Loriaux and Cassassa, 2013; Yao et al., 2012). Importantly, however, there has been no systematic assessment of whether these empirical relationships can be applied confidently across a range of locations and contexts (e.g. ice-dammed, moraine-dammed, supraglacial). Further, the relationships presented in Eqs. (1), (3) and (4) are based on the assumption that lake area and volume should scale predictably. Yet, glaciers are known to erode basins with complex morphometries, meaning that associated lakes may have complex bathymetries, and hence more unpredictable depth-area-volume relationships (e.g. Cook and Swift, 2012). Likewise, lake depths and hypsometries may be determined on a local scale by sedimentation or, where a lake develops supraglacially, by the underlying ice and debris surface. Empirical volume-area relationships can also give a misleading impression of the predictability of lake volumes because lake volume is dependent on area (Wang et al., 2012; Haeberli, 2015)), as has been noted also for volume-area scaling relationships that predict glacier volume from surface area (Haeberli, in revision).. Hence, higher degrees of correlation between lake area and volume often mask the complexity of lake basin morphometry. In this study, we test the extent to which lake depth, area and volume are correlated under a range of scenarios based on a compilation of published ~~measurements~~ datasets of lake basin morphometries. In particular, we examine the error between published lake volume ~~measurements~~ estimates based on interpolation from bathymetric measurements compared to volumes calculated by using the empirical relationships of O'Connor et al. (2001), Evans (1986), and Huggel et al. (2002).

Commented [SC4]: This is the most substantial change made in response to interactive comment by Prof. Haeberli.

2 Data and Methods

We have compiled a dataset of glacial lake areas, average depths and bathymetrically derived volumes from published articles and reports (Supplementary Tables 1 and 2). The dataset comprises 42 lakes with measured lake areas and mean depths (Supplementary Table 1), most of which (36) were reported in the publications themselves. The remainder were derived by the current authors from published bathymetric maps, which were georeferenced in ArcMap and then digitised; mean depth measurements were then interpolated from the contour data. Some of these data represent duplicate readings from individual sites where repeat measurements have been made over several years. When these duplicates are removed, the dataset comprises 30 lakes (Table 1). Lake area and depth data presented in Huggel et al. (2002) represent a further 15 ~~datapoints~~data points, and we derive empirical relationships between lake area and depth with and without duplicates, and with and without the data of Huggel et al. (2002) included (Table 1). Empirical relationships are derived by fitting power-law functions to the area-depth data plotted on logarithmic scales. We have not used depth data derived from dividing bathymetrically derived volumes over measured areas to avoid the issue of auto-correlation.

There are 69 lakes with measured areas and volumes calculated from bathymetric data (Table 2). As with the area-depth data, most of these ~~measurements~~ data points (63) were reported directly in the literature; the remainder were derived from interpolated bathymetric map data by the current authors. Removal of duplicate sites reduces the number of ~~datapoints~~data points to 49. The area and volume data of O’Connor et al. (2001) represent a further 6 sites, and again, empirical relationships are derived with and without the duplicate sites and data from O’Connor et al. (2001) by fitting a power-law function to the data.

Derivation of power-law functions for area-depth and area-volume data is performed in conjunction with a calculation of the coefficient of determination, r^2. The dataset includes some sites where lake depths, areas and volumes have been measured or estimated at different times. We present relationships in Table 1 that both include these duplicate ~~measurements~~data points, and exclude them where only the most recent measurement or estimate is included. Hence, we account for the influence of duplicate ~~measurements~~ data points skewing the dataset. Other studies (e.g. Loriaux and Casassa, 2013) have included duplicates to derive their area-depth and area-volume relationships. Likewise, we include relationships derived purely from Huggel et al. (2002) data or from our compiled data, and for combinations of these datasets. This allows comparison between our data and those of Huggel et al. (2002), whilst also acknowledging that these datasets could reasonably be combined. Since our data are sourced from other studies, we do not account for seasonal variations (e.g. melt season versus winter) in water depth, area and volume, but we acknowledge that this could influence these measurements to some extent.

Commented [SC5]: Reviewer J. Herget asked us to consider the impact of variability in lake size over time.

High r^2 values lend support to the possibility of a relationship between two variables, but outliers can exist in datasets even where the r^2 value is high. Hence, in order to investigate the extent to which existing empirical relationships (Eqs. (1), (3) and (4)) are able to estimate accurately the volume of individual lakes, we provide a quantification of error. Huggel et al. (2004) calculated error (%) as the difference between “measured” and calculated volumes divided by the calculated volume, whereas Allen et al. (2009) calculated error (%) as the difference between “measured” and calculated volumes, divided by the “measured” volume. It should be noted that lake volumes cannot truly be measured because they involve some degree of interpolation from bathymetric measurements (Haeberli, 2015). We adopt the approach of Huggel et al. (2004) in dividing by calculated volume, because the method of Allen et al. (2009)

generates varying error values depending on whether the bathymetrically derived (i.e. “measured”) lake volume is less than or greater than the calculated volume.

3 Results

3.1 Lake area versus depth

Fig. 1 presents all of the lake area against measured mean depth data from Huggel et al. (2002) and from the range of data compiled in this study, with best-fit line equations and r^2 values shown for both. O’Connor et al. (2001) derived their area-volume relationship (Eq. (1)) from a plot of area versus volume (their Fig. 18), meaning that no depth data are available to plot on Fig. 1 from their study. Table 1 presents a summary of the resulting depth-area relationships and the volume-area relationships, the latter having been derived following Huggel et al. (2002) (i.e. the transition from Eq. (2) to (3)).

The re-plot of data presented in Huggel et al. (2002) differs from that presented in their study (their Fig. 1). Indeed, the one significant outlier in their graph actually plots very close to the best-fit line for their data, and two points that appear in their Table 2 do not appear in their Fig. 1. Hence, overall, the r^2 value for the data presented in Huggel et al. (2002) increases to 0.95 (from 0.91 as stated in their study), and the best-fit line equation, $D=0.1217A^{0.4129}$, differs slightly from Eq. (2) (Table 1). Accordingly, Eq. (3) for lake volume becomes $V=0.1217A^{1.4129}$. We note, however, that Huggel et al. (2002) also employed a bias correction procedure in their study, although this was not described.

Plotting all available data compiled in this study (including duplicate readings for some sites where there are data for two or more measurement periods) reveals a low r^2 value of 0.38, demonstrating that there is significant variability in lake depth for any given area. For example, Fig. 1 illustrates that a lake with an area of between ~4,000,000 to 5,000,000 m^2 could have a mean depth of between ~15 and 150m. Further, there are many visually obvious outliers in the dataset presented in Fig. 1 that deviate ~~significantly~~ greatly from the best-fit line of Huggel et al. (2002). If duplicate sites are removed (leaving only the most recently measured lake areas and depths), the r^2 value increases to 0.60 because the influence of individual lakes is reduced.

Commented [SC6]: Reviewer 1 asked us how we identified outliers in Fig 1. We clarified this issue here.

Since the data of Huggel et al. (2002) plot with a high r^2 value, their combination with our data, both where duplicates are included or excluded, increases the r^2 value for best fit lines to 0.57 and 0.74 respectively (Table 1). Overall, our combined data demonstrate significant variability in the relationship between lake area and depth, and hence between area and volume.

3.2 Lake area versus volume

O'Connor et al. (2001) derived their lake area-volume relationship (Eq. (1)) directly from measured lake areas and lake ~~volumes~~volumes derived from measured bathymetries. Fig. 2 presents lake area against volume for the data compiled in this study and in O'Connor et al. (2001). For reference, a line representing the lake volumes predicted by using Huggel et al.'s (2002) relationship (Eq. (3)) is also plotted in Fig. 2. Table 2 presents a summary of these relationships, as well as combinations of these datasets with and without the inclusion of duplicate ~~measurements~~ data points ~~of~~ from individual lakes.

A re-plot of O'Connor et al.'s (2001) data reveals a high r^2 value of 0.97 (Fig. 2, Table 2), indicating a strong dependence of lake volume on area. Fig. 2 demonstrates that there is also a strong relationship between lake area and volume for the data compiled in this study, with a high r^2 value of 0.91. Both the data of O'Connor et al. (2001) and in this study plot in close association with the best-fit line representing the lake area-volume relationship of Huggel et al. (2002). The r^2 value increases once duplicate lake ~~measurements~~ data points are removed, largely because of outliers in the dataset that also happen to be duplicate ~~measurements~~ data points (Table 2).

Despite the visually close association of most of the data points in Fig. 2 and the relatively high r^2 values shown in Table 2, there are a number of outliers in the dataset that become more apparent when the upper and lower ends of the dataset are curtailed (essentially, zooming-in on the mid-range of the dataset). For example, at a lake area of ~300,000 m^2, the corresponding lake volume could be as little as 2.2 million m^3 or as much as 21.3 million m^3. Likewise, at ~500,000 m^2 the volume could be between ~10 to 77.3 million m^3, and at ~4 million m^2 to 5 million m^2 the volume could be between ~53 to ~770 million m^3. Hence, there can be order-of-magnitude differences in volume for a given lake area.

3.3 Error between modelled and ~~measured~~ bathymetrically derived lake volume

Table 3 presents a measure of error between ~~measured~~ bathymetrically derived volumes and the volumes calculated using Eqs. (1), (3) and (4). To identify lakes whose volumes are not well predicted by Eqs. (1), (3) and (4), we categorise the calculated errors such that an error between ~~measured~~ bathymetrically derived and modelled volumes of +/- 25-49% is considered to represent a lake with a '*moderately unpredictable*' volume (highlighted yellow), +/- 50-99% error is considered to be a lake with '*unpredictable*' volume (highlighted orange), and an error of beyond +/- 100% is considered to represent a lake with '*highly unpredictable*' volume (highlighted red).

Table 3 demonstrates that the use of O'Connor et al.'s (2001) volume calculation leads to very large errors in most cases. The relationships of Huggel et al. (2002) and Evans (1986) perform better in general, although there are exceptions. For ease of interpretation, we ascribe error scores in the right hand columns. For any individual ~~measurement~~estimate, errors beyond +/- 100% are scored 3, errors between +/- 50-99% are scored 2, errors between +/- 25-49% are scored 1, and errors of +/- 0-24% are scored 0. The first of the right-hand columns is the sum of these scores from all three methods of volume estimation. A combined score of 7-9 is considered '*highly unpredictable*', a score of 4-6 is considered '*unpredictable*', and a score of 0-3 is considered to be '*reasonably predictable*'.

Since the method of O'Connor et al. (2001) seems to over-estimate greatly lake volumes in most cases, even when the other methods are reasonable predictors, the furthest right-hand column presents error scores based only on Huggel et al. (2002) and Evans (1986). Combined scores of 5-6 are considered '*highly unpredictable*', and scores of 3-4 are considered '*unpredictable*'. Scores of 0-2 are considered to be '*reasonably predictable*'. The results of these two right-hand columns are broadly comparable, identifying the same lakes in most cases.

Table 3 reveals several lakes with 'highly unpredictable' lake volumes including Hooker, Ivory Lake, Laguna Safuna Alta, Lake No Lake, Nef, and Ngozumpa 4. A group with 'unpredictable' volumes includes Checquiacocha, Gelhaipuco, Hazard / Steele Lake, Imja (in 1992), Maud Lake, Mt Elbrus, Mueller, Ngozumpa, Petrov, Quitacocha, and Tam Pokhari.

The relationship of O'Connor et al. (2001) out-performs those of Huggel et al. (2002) and/or Evans (1986) in a few cases including, including many of the 'highly unpredictable' lake volumes. Specifically, these are Hooker, Imja (in 1992), Ivory, Laguna Safuna Alta, Lake No Lake, Miage, MT Lake, Ngozumpa 4, Quitacocha, and Tam Pokhari.

4 Discussion

4.1 Performance of existing relationships

We have compiled a dataset of ~~measured~~ Alpine glacial lake areas, depths and volumes in order to evaluate critically the use of existing empirical relationships for the estimation of glacial lake volumes. The plot of lake area against mean lake depth (Fig. 1) reveals a significant degree of scatter, indicating that lake area and depth do not always scale predictably. Hence, empirical relationships for estimating lake volume that are founded upon a strong correlation between lake area and depth (e.g. that of Huggel et al., 2002) should be used with caution. Equally, Fig. 2 shows that there are also significant outliers in the dataset of measured areas ~~and~~ against bathymetrically derived volumes, even though one might expect some degree of auto-correlation between area and volume (Huggel et al., 2002; Mergili and Schneider, 2011).

In general, the empirical relationships derived by Evans (1986) and Huggel et al. (2002) perform better at estimating lake volumes than the relationship of O'Connor et al. (2001) (Table 3). These relationships are also more robust because they are derived from a relationship between lake depth and area, and hence are not affected by auto-correlation (Huggel et al., 2002; Mergili and Schneider, 2011). The re-plotting of lake depth and area data from Huggel et al. (2002) reveals a slightly different relationship to that reported in the original study (Table 1), although it will make little difference to calculated volumes if either the original or revised relationship is used. As McKillop and Clague (2007) explain, the O'Connor et al. (2001) relationship is derived from a dataset of lakes whose volumes are large for their relatively small areas. This is a consequence of moraine dam emplacement on steep slopes, giving comparatively large depths and volumes. Hence, the relationship of O'Connor et al. (2001) should be expected to overestimate lake volume with increasing lake area in most situations. Table 3 reveals that the relationship of O'Connor et al. (2001) out-performs the other empirical relationships for Hooker, Imja (in 1992), Ivory, Laguna Safuna Alta, Lake No Lake, Miage, MT Lake, Ngozumpa 4, Quitacocha, and Tam Pokhari. These lakes may be unusually deep for their respective surface areas, as were the lakes ~~measured~~ investigated by O'Connor et al. (2001).

4.2 Geomorphometric controls of lake variability

Fig. 1 shows that glacial lakes can be exceptionally deep or exceptionally shallow for any given surface area. There are several reasons that may account for this depth variability. First, glaciers achieve different levels of erosion and sediment flux, meaning that the depth of erosion of glacial basins (overdeepenings) within which lakes sit, and the height of moraine dams that impound lakes, can be highly variable (e.g. Cook and Swift, 2012). Secondly, shallow lakes may develop on top of stagnant or stagnating ice (Yao et al., 2012), or where lake basins become progressively filled with sediment (Allen et al., 2009) meaning the evolution of such lakes can vary widely even if their starting morphology is the same. Thirdly, the presence or absence of a lake outlet, and the elevation of that outlet or notch with respect to the glacier terminus bed elevation, will have a significant control on the depth of water that is allowed to accumulate in any lake basin.

Some of the lakes with ‘highly unpredictable’ or ‘unpredictable’ volumes (Table 3) share common characteristics, which may prove instructive when deciding upon an appropriate empirical relationship with which to estimate the volume of different lake types. Firstly, Mueller, Ngozumpa, Petrov and Mt Elbrus are all lakes that are either situated (partly or wholly) on top of stagnant or relict glacier ice, or have large subaqueous ice bodies that protrude into the lake from the glacier terminus. At Mueller Glacier, Robertson et al. (2012) detected an exceptionally long (510 m) subaqueous ice ramp that covered ~20 % of the lake surface area beneath the water line, and Röhl (2005) suggested that the Mueller lake bed was ice-cored. At Ngozumpa Glacier, the lake is developing supraglacially from the coalescence of surface melt ponds on the debris-covered glacier surface (Benn et al., 2001; Thompson et al., 2012). Petrov lake is developing at the glacier terminus where it appears that an ice-cored medial moraine is mostly submerged beneath the lake surface, effectively splitting the lake into two sub-basins (Jansky et al., 2009, 2010; Engel et al., 2012). The southeastern lake of Mt Elbrus is reported by Petrakov et al. (2007) to have a bed composed of stagnant ice. ~~Mool et al.~~ICIMOD (2001, 2011) categorised supraglacial lakes separately to moraine-dammed lakes, noting that there was a continuum between lake forms as supraglacial ponds evolved to supraglacial lakes, through to moraine-dammed lakes. We suggest that, because of the underlying ice content, supraglacial lakes are relatively shallow compared to moraine-dammed lakes, and hence existing relationships for the prediction of lake volume tend to over-estimate lake volume.

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The second grouping includes lakes situated within basins with complex bed topography, some of which may be related to focussing of glacial erosion. Hooker Lake had a greater than predicted volume in 1995 and 2002, but not in 2009. Comparison of glacier terminus position and bathymetric maps in Robertson et al. (2013) indicates that in 1995, the glacier terminus was retreating out of a deep basin. By 2002, the glacier had retreated to the position of a deep notch in the bed profile. At Ivory Glacier, lake volume was significantly under-predicted for 1976 and 1986, although less so for 1980. Examination of lake long-profiles in Hicks et al. (1990) indicates that in 1976 and 1986, the glacier had recently retreated into a deep basin. The lake in these situations is disproportionately deep at one end, and shallower toward the moraine dam, which means that the lake volume is not well-predicted. Ivory Glacier in 1986 terminated in a nested overdeepening (a basin within a basin). This complex lake basin morphometry may thus yield lake volumes that are under-predicted by existing empirical relationships. Tam Pokhari, Checquiacocha, Maud Lake, and arguably Ivory Lake, all appear in places where glacial erosion may have been particularly intense, and hence might be expected to generate particularly deep basins with lake volumes that are not well-predicted by existing empirical relationships (Table 3). Tam Pokhari, Checquiacocha and Ivory Lake appear at the base of what would have been steep icefalls with greater potential for erosion and sediment transfer (cf. Cook et al., 2011). Maud Lake is located in what would have been a tributary glacier junction where erosion would have been intense as a consequence of enhanced ice flux (cf. Cook and Swift, 2012).

A third identifiable situation is represented by Hazard / Steele Lake, which formed when a glacier advanced across a valley (Collins and Clarke, 1977; Clarke, 1982). Table 3 reveals that empirical relationships underestimate its volume. We make the tentative suggestion that the morphometry of lake basins such as this, where the host valley has been shaped to some extent by fluvial and mass movement processes before glacier advance, means that their volumes are not well predicted by empirical relationships based on measurements of lakes that occupy basins of purely glacial origin. Lake No Lake may also fit within this category because it occupies a valley situated between two glaciers (Geertsema and Clague, 2005).

The remaining outliers from Table 3 are lakes with a range of site-specific characteristics that make their volumes hard to predict, or represent situations where there is no clear reason for their unusual volumes. Some of these outliers are related to apparently unusual situations (compared to lakes upon which empirical relationships have been based). Specifically, Ngozumpa 4 is an ice-marginal moraine-dammed lake that is reported by Sharma et al. (2012) to have a deep crevice at its base, giving it an unusually deep bed; Laguna Safuna Alta has a complex history of lake level change, involving modification by engineering works, and a suspected increase in moraine dam permeability as a consequence of an earthquake in 1970 (Hubbard et al., 2005), although it is not clear why it should be unusually deep. Quitacocha and Gelhaipuco lakes are both moraine-dammed and their volumes are underestimated by empirical relationships. Again, it is unclear why this should be the case.

4.3 Relationships by region

An intriguing result from our analysis is that lakes within similar geographical areas do not necessarily have equally predictable lake volumes. A number of studies have adapted existing empirical relationships by adding data from specific regions (e.g. Loriaux and Cassassa, 2013), or by generating completely new relationships from known lake properties for specific regions in favour of adopting existing empirical relationships (e.g. Yao et al., 2012). There is some merit in this approach because, for example, the volumes of many of the Himalayan glacial lakes listed in Table 3 are consistently under-predicted by existing empirical formulae, indicating regional controls on lake volumes. Yet, the dataset compiled in this study reveals a number of examples where lakes in the same region can have very different degrees of volume predictability. For example, the Hooker and Mueller lakes are only ~1.8 km apart, yet empirical relationships under-predict the volume of Hooker lake, and over-predict the volume of Mueller lake. The volume of Tasman lake, <2 km to the east of Hooker lake, is well-predicted by the relationships of Huggel et al. (2002) and Evans (1986) (Table 3). It should not, therefore, be assumed that empirical relationships derived for specific regions will perform any better than existing relationships derived from a range of sites. It is more likely that lake origin and context are key in determining how predictable lake volume might be, and what type of empirical relationship to use to make that prediction.

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4.4 Relationships by lake type

In order to better understand lake growth and the application of empirical relationships, we have re-plotted the data according to lake context (Fig. 3), and developed a corresponding conceptual model for each (Fig. 4). One of the striking results of our error analysis (Table 3) was that growing supraglacial lake volumes are not well-predicted by existing empirical relationships. Supraglacial lake evolution has been examined in a number of studies (e.g. Kirkbride, 1993; Sakai et al., 2000, 2003, 2009; Benn et al., 2001; Thompson et al., 2012) with small ponds developing through melting of exposed ice faces, and large lakes expanding primarily through calving. Sakai et al. (2009) suggested that wind-driven currents of relatively warm water were important for lake growth and calving, and hence, lake fetch (defined as the maximum lake length along the axis of glacier flow) represents a primary control on lake evolution. Their work demonstrated that supraglacial lakes expand by calving once lake fetch exceeds ~80 m, and that subaqueous thermal undercutting of ice cliffs occurred for fetches that exceed 20-30 m when the water temperature was 2-4 °C. We hypothesise that, at least initially, supraglacial ponds and lakes tend to grow areally at a much faster rate than their depths do through the melting of underlying ice (Fig. 4). It is quite likely that as these lakes evolve to become moraine-dammed forms with little or no lake-bottom ice, volume will tend to increase linearly with area, as found for most moraine-dammed lakes in our compiled dataset (Fig. 3b). This assertion is borne out to some extent by a plot of the limited available area-volume data for growing supraglacial lakes (equivalent data are lacking for supraglacial ponds) (Fig. 3a). These data fit a power-law function of the form $V = 3 \times 10^{-7}A^{1.239}$ with an r^2 value of 0.99, although it should be stressed that this is based on very few datapoints, several of which are from Petrov Lake. Fig. 3d shows that growing supraglacial lakes form a distinct population when compared to other datasets of ice-dammed lakes, and a selection of moraine-dammed lakes that have evolved from supraglacial lakes (including Imja Tsho, Lower Barun, Tsho Rolpa and Thulagi). Notably, their volume increases only at a slow rate with increased area, probably because they are relatively shallow. However, Fig. 3d also illustrates that the area-volume relationship for more mature supraglacial lakes deviates significantly from that of the growing supraglacial lakes. Here, lake volume increases more rapidly, perhaps as a consequence of increased calving rate associated with deeper water as the lake-bottom ice melts out. However, it is unclear from these limited data which of these two trajectories shown on Figs. 3d and 4, if either, other examples of evolving supraglacial lakes should be expected to follow. We suggest that it would be particularly valuable for future studies to focus on gathering empirical data on the morphometry of supraglacial lakes to help address this issue. Certainly, caution should be exercised when applying existing empirical relationships to predict the volume of growing supraglacial lakes.

In contrast, lakes that have evolved toward the moraine-dammed end-member appear to have more predictable volumes. Fig. 3b illustrates that most moraine-dammed lake volumes scale linearly with increasing area. Likewise, the available data indicate that ice-dammed lakes may evolve predictably, such that lake volume grows exponentially with increasing lake area (Fig. 3c and 4).

5 Conclusions

The ability to estimate accurately the volume of glacial lakes is important for the modelling of glacial lake outburst flood (GLOF) magnitudes and runout distances. Direct ~~measurement~~

estimation of lake volume in the field through detailed bathymetric surveying is a potentially difficult and dangerous undertaking. Hence, many studies rely on empirically derived relationships that allow the estimation of lake volume from a measurement of lake area, which is readily gained from satellite imagery. However, there has been no systematic assessment of the performance of these existing empirical relationships, or the extent to which they should apply in different glacial lake contexts. In this study, we have compiled a comprehensive dataset of glacial lake area, depth and volume in order to evaluate the use of three well-known empirical relationships, namely those of Huggel et al. (2002), Evans (1986) and O'Connor et al. (2001).

Our first key finding is that lake depth and area are only moderately correlated (with an r^2 value of 0.38), and that for any given lake area there may be an order of magnitude difference in mean lake depth. Equally, a plot of lake area against volume revealed an r^2 value of 0.91, but with several distinct outliers in the dataset. Again, for any given lake area there may be order-of-magnitude differences in lake volume. These results indicate that any relationship for predicting lake volume founded on the notion that lake area and depth should scale predictably may not always estimate lake volume reliably.

Our second key finding is that two of the three existing empirical relationships (those of Huggel et al., 2002 and Evans, 1986) give reasonable approximations of lake volume for many of the lakes examined in this study, but that there are several lakes whose volumes are over- or under-estimated by these relationships, sometimes with errors of as much as 50 to over 400 %. The relationship of O'Connor et al. (2001) is only reliable in a handful of cases, seemingly where lakes are unusually deep.

Many of the lakes whose volumes are not well predicted by empirical relationships fall into distinct groups, meaning that it is possible to identify situations where it could be inappropriate to apply empirical relationships to estimate lake volume, important for robust assessments of GLOF risk. Specifically, these groups include (i) lakes that are developing supraglacially, which tend to grow areally by calving and edge melting, but which are shallow due to the presence of ice at the lake bed or of ice ramps protruding from calving faces; (ii) lakes that occupy basins with complex bathymetries comprising multiple overdeepenings, or which are particularly deep due to carving by intense erosion (e.g. at the base of an icefall or at former tributary glacier junctions); and (iii) lakes that form in deglaciated valleys (e.g. when glaciers advance to block valley drainage). Other outliers represent a range of unusual cases where site-specific factors complicate the relationship between lake area and volume.

Ultimately, we develop a conceptual model of how volume should be expected to change with increasing area for a range of lake contexts, based on re-plotting of the data according to lake type. Specifically, these include moraine-dammed, ice-dammed, supraglacial ponds and supraglacial lakes. We suggest that further measurements of the bathymetry of growing supraglacial ponds and lakes would be very valuable in developing robust relationships for the prediction of their evolving volumes.

Acknowledgements

We gratefully acknowledge the interactive comment from Wilfried Haeberli, which made us think critically about our use of terminology, and also about empirical lake area-volume relationships. Likewise, we thank Jürgen Herget and an anonymous reviewer for their thoughtful and constructive reviews. We are particularly grateful to Jürgen Herget for providing electronic and hard copies of an edited volume that we would not otherwise have been able to access. We thank Vladimir Konovalov for providing further reports pertinent to this study.

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Table 1. Summary of relationships derived from measured lake area and depth data.

Relationship	Number of datapoints (n)	r^2 value	Range in Area (m^2)	Range in Depth (m)	Depth (m) vs. Area (m^2) relationship	Volume (m^3) vs. Area (m^2) relationship
Re-plot of Huggel et al. (2002) data	15	0.95	3500 - 6 $\times 10^6$	2.9 – 83.3	$D = 0.1217 A^{0.4129}$	$V = 0.1217 A^{1.4129}$
Compilation of data in this study including duplicate sites	42	0.38	35900 - 172 $\times 10^6$	6.2 – 150.1	$D = 0.5057 A^{0.2884}$	$V = 0.5057 A^{1.2884}$
Compilation of data in this site excluding duplicate sites	30	0.60	35900 – 172 $\times 10^6$	6.2 – 150.1	$D = 0.1746 A^{0.3725}$	$V = 0.1746 A^{1.3725}$
Compilation of data in this study including duplicate sites plus Huggel et al. (2002) data	57	0.57	3500 - 172 $\times 10^6$	2.9 – 150.1	$D = 0.3211 A^{0.324}$	$V = 0.3211 A^{1.324}$
Compilation of data in this study excluding duplicate sites	45	0.74	3500 - 172 $\times 10^6$	2.9 – 150.1	$D = 0.1697 A^{0.3778}$	$V = 0.1697 A^{1.3778}$

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plus Huggel et al. (2002) data

Table 2. Summary of relationships derived from measured lake area and bathymetrically derived volume data.

Relationship	Number of data points (n)	r^2 value	Range in Area (m^2)	Range in Volume (x 10^6 m^3)	Volume (m^3 x 10^6) vs. Area (m^2) relationship
Re-plot of O'Connor et al. (2001)	6	0.97	6120 - 70000	0.027 – 0.9	$V = 3 \times 10^{-7} A^{1.3315}$
Compilation of data in this study including duplicate sites	69	0.91	28000 – 19.5 x 10^6	0.143 – 2454.6	$V = 2 \times 10^{-7} A^{1.3719}$
Compilation of data in this study excluding duplicate sites	49	0.94	40000 – 19.5 x 10^6	0.2 – 2454.6	$V = 7 \times 10^{-8} A^{1.4546}$
Compilation of data in this study including duplicate sites plus O'Connor et al. (2001) data	75	0.94	6120 - 19.5 x 10^6	0.027 – 2454.6	$V = 2 \times 10^{-7} A^{1.3721}$
Compilation of data in this study excluding duplicate sites plus O'Connor et al. (2001) data	55	0.96	6120 - 19.5 x 10^6	0.027 – 2454.6	$V = 1 \times 10^{-7} A^{1.434}$

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Table 3. Comparison of ~~measured~~ bathymetrically derived lake volumes with those calculated using existing empirical relationships. Errors are calculated according to Huggel et al. (2004) and coded such that error between ~~measured~~ bathymetrically derived and modelled volumes of +/- 25-49% is considered 'moderately unpredictable' volume (~~highlighted yellow~~*italic*), +/- 50-99% error is considered 'unpredictable' (~~highlighted orange~~**bold**), and an error of beyond +/- 100% is considered 'highly unpredictable' (~~highlighted red~~***bold-italic***). Error scores are provided in the right hand columns for ease of interpretation. Errors beyond +/- 100% are scored 3, errors between +/- 50-99% are scored 2, errors between +/- 25-49% are scored 1, and errors of +/- 0-24% are scored 0. The first of the right-hand columns is the sum of these scores from all three methods of volume estimation, and the furthest right-hand column is the sum of scores from the models of Huggel et al. (2002) and Evans (1986).

Site, survey date, reference(s)	~~Measured~~ Bathymetrically derived volume (x 10^6 m^3)	Huggel et al. (2002) volume	Evans et al. (1986) volume	O'Connor et al. (2001) volume	Huggel et al. (2002) error (%)	Evans et al. (1986) error (%)	O'Connor et al. (2001) error (%)	Error score based on all three volume estimate methods	Error score based on Huggel et al. (2002) and Evans (1986)
Abmachimai Co, Tibet, 1987, Sakai et al. (2012)	19.0	15.1	14.7	54.6	*25.7*	*29.5*	**-65.2**	4	2
Ape Lake, 1984-85, Gilbert and Desloges (1987)	92.8	146.4	161.4	1302.1	*-36.6*	*-42.5*	**-92.9**	4	2
Bashkara, 2008, Petrakov et al. (2012)	1.0	1.0	0.9	1.5	-3.8	15.3	*-32.5*	1	0

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Briksdalsbreen, 1979, Duck and McManus (1985)	0.3	0.4	0.3	0.5	*-30.1*	-12.2	*-39.7*	2	1
Briksdalsbreen, 1982, Duck and McManus (1985)	0.3	0.4	0.4	0.5	-33.7	-16.4	*-42.1*	1	0
Cachet II, 2008-9, Casassa et al. (2010)	200.0	250.5	284.7	2769.6	-20.2	*-29.8*	**-92.8**	3	1
Chamlang south, Nepal, 2009, Sawagaki et al. (2012)	35.6	28.3	28.4	130.2	*26.0*	*25.3*	**-72.7**	4	2
Checquiacocha, 2008, Emmer and Vilimek (2013)	12.9	7.8	7.3	21.9	**64.7**	**76.2**	**-41.4**	6	4
Dig Tsho, Nepal, pre-2001, ~~Mool et al.~~ICIMOD (2001)	10.0	12.9	12.4	43.7	-22.3	-19.2	**-77.1**	2	0

Gelhaipuco, 1964, ~~Mool et al.~~ICIMOD (2001)	25.5	14.7	14.2	52.3	**73.6**	**79.2**	**-51.3**	6	4
Goddard, 1994, Clague and Evans (1997)	4.0	3.8	3.4	8.1	6.5	18.8	**-50.5**	2	0
Godley, 1994, Warren and Kirkbride (1998)	102.0	73.2	77.6	492.3	22.2	15.6	**-81.5**	2	0
Godley, 1994, Allen et al. (2009)	85.7	70.1	74.2	463.9	*39.4*	*31.5*	**-79.3**	4	2
Hazard / Steele, 1974, Collins and Clarke (1977)	14.0	28.7	28.9	133.2	**-51.3**	**-51.5**	**-89.5**	6	4
Hazard / Steele, 1979, Clarke (1982)	19.6	48.6	50.3	277.5	**-59.6**	**-61.0**	**-92.9**	6	4
Hidden Creek Lake, 1999-2000, CUNICO (2003)	21.2	26.1	26.1	116.6	-18.6	-18.7	**-81.8**	2	0
Hooker, 1995, Allen et al. (2009)	41.0	20.8	20.5	84.7	**97.6**	***100.0***	**-51.6**	7	5

Hooker, 2002, Allen et al. (2009)	59.0	29.7	29.9	139.3	**99.0**	**97.4**	**-57.6**	6	4
Hooker, 2009, Robertson et al. (2013)	50.0	45.7	47.2	254.6	9.5	6.0	**-80.4**	2	0
Imja, Nepal, 1992, Sakai et al 2012	28.0	16.7	16.3	62.5	**67.9**	**72.1**	**-55.2**	6	4
Imja, Nepal, 2002, Sakai et al 2012	35.8	28.0	28.1	128.5	*27.9*	*27.4*	**-72.1**	4	2
Imja, Nepal, 2009, Sakai et al 2012	35.5	34.9	35.5	175.0	1.6	-0.1	**-79.7**	2	0
Imja, Nepal, pre-1992, Yamada and Sharma (1993), Yao et al. (2012)	61.6	47.7	49.3	270.2	*29.3*	24.9	**-77.2**	3	1
Imja, Nepal, 2012, Somos-Valenzuela et al., 2013	63.8	45.1	46.6	250.5	*41.3*	*37.0*	**-74.5**	4	2
Ivory, 1976, Hicks et al. (1990)	1.5	0.8	0.7	1.1	**73.1**	***110.0***	*28.9*	6	5

Ivory, 1980, Hicks et al. (1990)	2.0	1.3	1.1	1.9	**57.8**	**86.9**	4.2	4	4
Ivory, 1986, Hicks et al. (1990)	3.5	1.7	1.4	2.7	***112.7***	***148.3***	*29.9*	7	6
Laguna Safuna Alta, 2001. Hubbard et al. (2005)	21.3	7.5	7.0	20.9	***182.5***	***202.7***	1.9	6	6
Lake No Lake, 1999, Geertseema & Clague (2005)	720.0	338.5	391.3	4228.1	***112.7***	**84.0**	**-83.0**	7	5
Lapa, 2001, Petrakov et al. (2007)	0.2	0.4	0.3	0.4	*-43.9*	*-28.6*	*-49.3*	3	2
Lapa, 2006, Petrakov et al. (2007)	0.1	0.2	0.2	0.2	*-33.4*	-12.8	*-34.8*	2	1
Leones, 2001, Harrison et al., 2008; Loriaux & Casassa, 2013	2454.6	2338.4	3014.1	64139.4	5.0	-18.6	**-96.2**	2	0
Llaca, 2004, Emmer & Vilimek 2013	0.3	0.4	0.3	0.5	*-32.9*	-15.2	*-40.9*	2	1

Longbasaba, 2009, Yao et al. 2012	64.0	45.6	47.1	254.1	*40.3*	*35.9*	**-74.8**	4	2
Lower Barun, Nepal, 1997, ~~Mool et al.~~ICIMOD (2001)	28.0	24.2	24.1	104.9	15.7	16.1	**-73.3**	2	0
Lugge, Bhutan, 2002 (Sakai et al., 2012)	58.3	43.0	44.3	234.3	*35.5*	*31.6*	**-75.1**	4	2
Maud Lake, 1994, Allen et al. (2009)	78.0	50.0	51.9	288.8	**56.0**	**50.4**	**-73.0**	6	4
Miage, 2003, Diolaiuti et al. (2005)	0.3	0.3	0.2	0.3	11.2	*42.8*	3.4	2	1
Mt Elbrus, 2000, Petrakov et al. (2007)	0.6	1.1	0.9	1.6	**-50.4**	*-40.8*	**-65.9**	5	3
MT Lake, 1982-3, Blown and Church (1985)	0.5	0.4	0.3	0.4	*31.6*	**67.0**	17.8	3	3
Mueller, 2002, Allen et al. (2009)	4.3	12.9	12.4	43.7	**-66.6**	**-65.3**	**-90.2**	6	4

Mueller, 2009, Robertson et al. (2012)	20.0	28.3	28.4	130.2	*-29.2*	*-29.6*	**-84.6**	4	2
Nef, 1998(?), Warren et al. (2001)	770.7	351.4	407.0	4455.6	***119.3***	**89.4**	**-82.7**	7	5
Ngozumpa 2, 2008, Sharma et al. (2012)	3.3	3.1	2.8	6.3	5.0	18.3	**-48.1**	2	0
Ngozumpa 3, 2008, Sharma et al. (2012)	10.6	10.3	9.8	32.2	2.5	7.9	**-67.1**	2	0
Ngozumpa 4, 2008, Sharma et al. (2012)	77.3	15.6	15.2	57.1	***395.1***	***409.3***	*35.4*	7	6
Ngozumpa, 2009, Thompson et al. (2012)	2.2	6.2	5.8	16.1	**-64.7**	**-61.7**	**-86.3**	6	4
Palcacocha, 2009, Emmer and Vilimek (2013)	17.3	13.9	13.4	48.7	24.5	*28.9*	**-64.4**	3	1
Palcacocha, 2009, Somos & McKinney (2011)	17.3	13.5	13.1	46.9	*27.9*	*32.6*	**-63.1**	4	2

Paqu Co, 1987, Sakai et al. (2012)	6.0	6.5	6.0	17.2	-8.1	-0.7	**-65.0**	2	0
Petrov Lake, 2003, Engel et al. (2012)	53.4	217.4	245.1	2268.6	**-75.4**	**-78.2**	**-97.6**	6	4
Petrov Lake, 2003, Jansky et al. (2010)	60.3	238.3	270.1	2581.6	**-74.7**	**-77.7**	**-97.7**	6	4
Petrov Lake, 1978, Sevatyanov and Funtikov, 1981; Loriaux and Cassasa (2013)	20.0	68.9	72.8	452.8	**-71.0**	**-72.5**	**-95.6**	6	4
Petrov Lake, 2006, Engel et al. (2012)	59.2	229.3	259.3	2445.0	**-74.2**	**-77.2**	**-97.6**	6	4
Petrov Lake, 2008, Engel et al. (2012)	62.0	236.1	267.5	2548.7	**-73.7**	**-76.8**	**-97.6**	6	4
Petrov Lake, 2009, Jansky et al. (2009)	64.0	237.9	269.6	2575.0	**-73.1**	**-76.3**	**-97.5**	6	4
Quangzonk Co, 1987, Sakai et al. (2012)	21.4	23.3	23.2	99.7	-8.2	-7.7	**-78.5**	2	0

Quitacocha, 2012, Emmer and Vilimek (2013)	3.2	1.9	1.6	3.3	**69.3**	**96.1**	-1.2	4	4
Rajucolta, 2004, Emmer and Vilimek (2013)	17.5	13.3	12.8	45.9	*31.6*	*36.6*	**-61.8**	4	2
Raphsthren, 1984, Sakai et al. (2012)	66.8	54.4	56.7	325.2	22.8	17.8	**-79.4**	2	0
Tam Pokhari, 1992, ~~Mool et al.~~ICIMOD (2001)	21.3	11.8	11.3	38.7	**80.3**	**88.4**	*-45.1*	5	4
Tararhua, 2008, Emmer and Vilimek (2013)	4.2	8.0	7.5	22.7	*-47.1*	*-43.5*	**-81.3**	4	2
Tasman, 2009, Robertson et al. (2012)	510.0	434.4	509.3	6003.9	17.4	0.1	**-91.5**	2	0
Thulagi / Dona, 1995, Sakai et al. (2012)	31.8	23.3	23.2	99.7	*36.3*	*37.1*	**-68.1**	4	2

Thulagi / Dona, 2009, Sakai et al. (2012)	35.4	31.5	31.9	151.8	12.1	10.9	**-76.7**	2	0
Tsho Rolpa,1993, Sakai et al. (2012)	76.6	55.0	57.4	329.9	*39.4*	*33.5*	**-76.8**	4	2
Tsho Rolpa, Nepal, 2009, Sakai et al. (2012)	85.9	63.6	66.9	404.4	*35.2*	*28.5*	**-78.7**	4	2
Tulsequah, 1958, Marcus (1960)	229.0	234.6	265.6	2525.1	-2.4	-13.8	**-90.9**	2	0

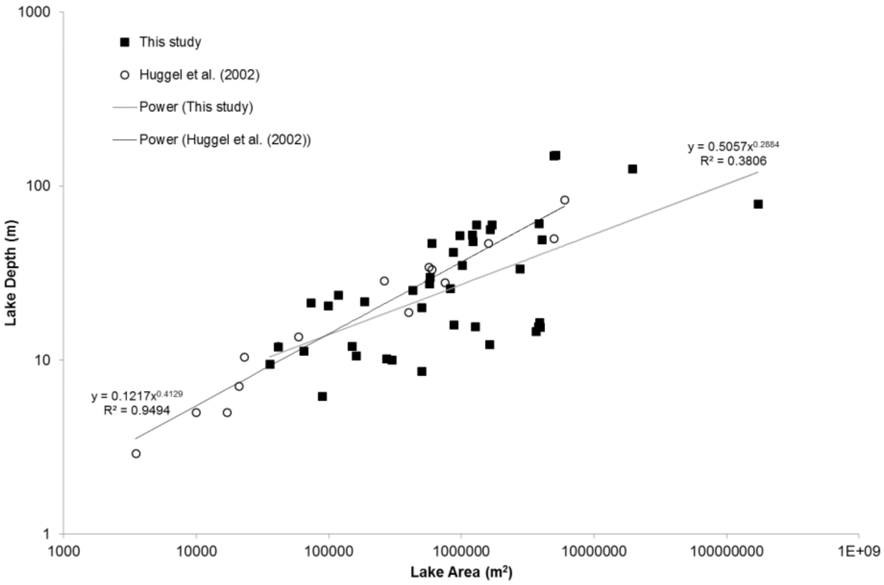

Figure 1. Plot of lake area versus depth for the data compiled in this study (including duplicate measurements of individual lakes) and the data presented by Huggel et al. (2002). Best-fit lines and corresponding equations and r^2 values are presented for both datasets.

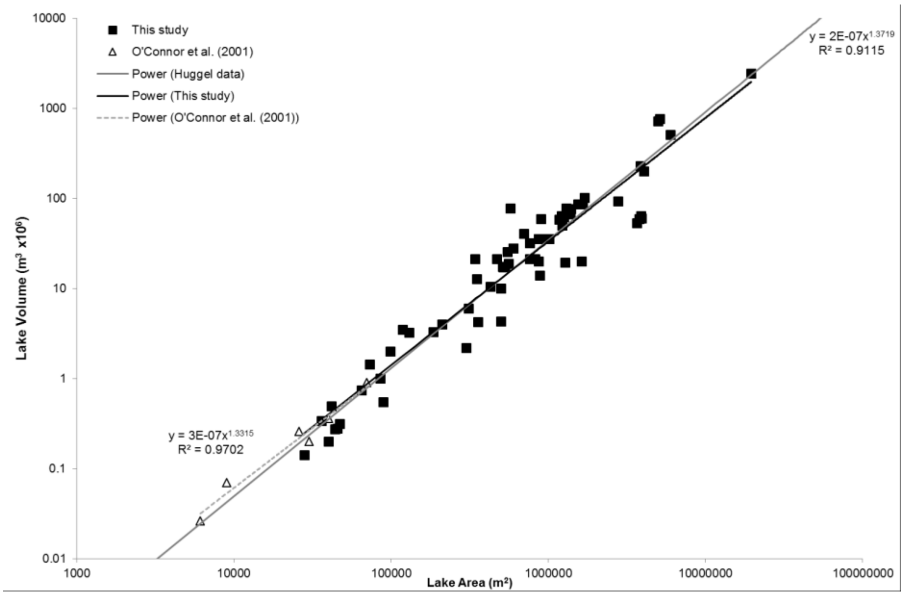

Figure 2. Plot of lake area against volume for the data compiled in this study and for the data presented by O'Connor et al. (2001). Best-fit lines and corresponding equations and r^2 values are presented for both datasets. The solid grey line represents the area-volume relationship of Huggel et al. (2002) (Eq. (3)) for reference.

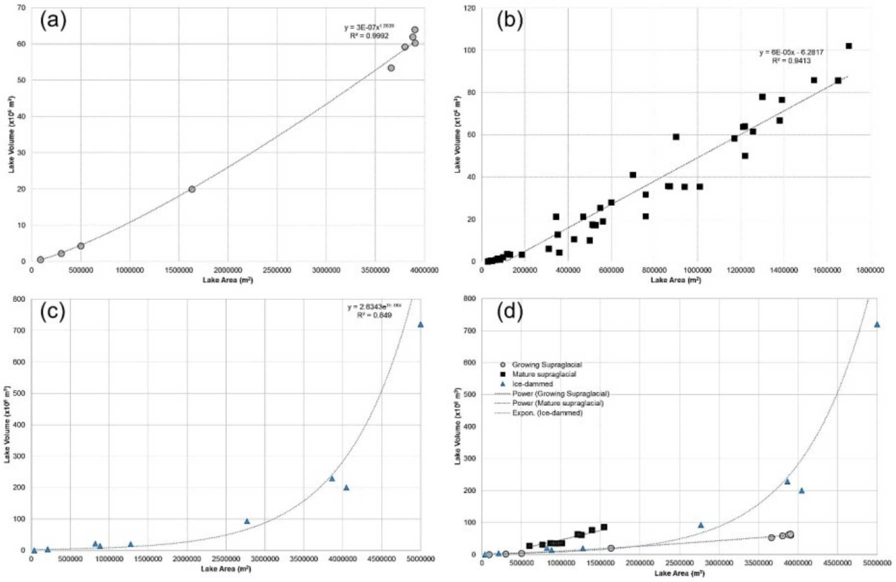

Figure 3. Plots of lake area-volume data according to different lake dynamic contexts. (a) Growing supraglacial lakes; (b) Moraine-dammed lakes excluding the largest lakes (Nef, Leones, Tasman) and extreme outliers (Ngozumpa 4) to facilitate comparison with the conceptual model presented in Fig. 4; (c) Ice-dammed lakes; (d) Growing supraglacial lakes compared to ice-dammed lakes and a selection of moraine-dammed lakes (labelled here as 'Mature supraglacial lakes'). Note that growing supraglacial lakes form a distinct population compared to other lake types.

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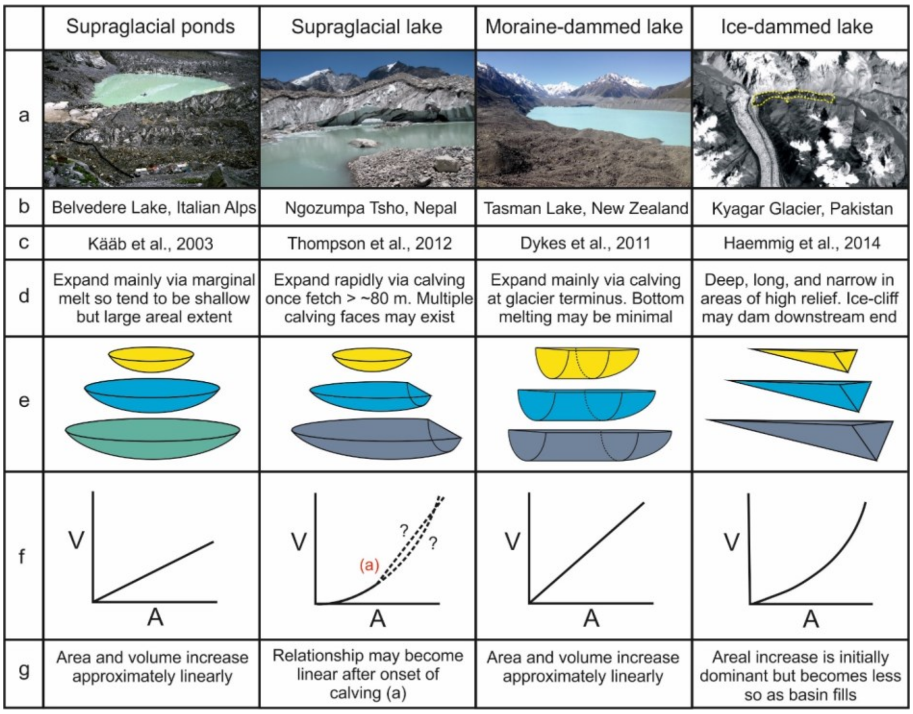

	Supraglacial ponds	Supraglacial lake	Moraine-dammed lake	Ice-dammed lake
a				
b	Belvedere Lake, Italian Alps	Ngozumpa Tsho, Nepal	Tasman Lake, New Zealand	Kyagar Glacier, Pakistan
c	Kääb et al., 2003	Thompson et al., 2012	Dykes et al., 2011	Haemmig et al., 2014
d	Expand mainly via marginal melt so tend to be shallow but large areal extent	Expand rapidly via calving once fetch > ~80 m. Multiple calving faces may exist	Expand mainly via calving at glacier terminus. Bottom melting may be minimal	Deep, long, and narrow in areas of high relief. Ice-cliff may dam downstream end
e				
f				
g	Area and volume increase approximately linearly	Relationship may become linear after onset of calving (a)	Area and volume increase approximately linearly	Areal increase is initially dominant but becomes less so as basin fills

Figure 4. Conceptual consideration of glacial lake evolution and its impact on volume-area relationships: a) imagery of typical lake types, b) example locations, c) associated reference for each lake type, d) notes on evolution style and morphology, e) idealised geometric shapes depicting evolution through time, f) idealised area-volume relationships, and g) notes on area-volume relationships. Photograph of Belvedere Lake by Jürg Alean (http://www.swisseduc.ch/glaciers/earth_icy_planet/glaciers13-en.html?id=16).

Supplementary Table 1: Compiled dataset of glacial lake areas and mean depths.

Glacier or Lake	Location	Survey Date	Study	Dam Type / Lake Context	Lake Area (m^2)	Mean Depth (m)
Ape Lake	British Columbia, Canada	1984-85	Gilbert and Desloges (1987)	Ice-dammed	2770606	33.5
Bashkara	Caucasus, Russia	2005?	Petrokov et al. (2007)	Moraine-dammed	65000	11.3
Brazo Rico, Perito Moreno	South Patagonia	pre-1999	Stuefer et al. (2007)	Ice-dammed	172000000	78.8
Cachet II	North Patagonia	2008-9	Casassa et al. (2010), Loriaux & Casassa (2013)	Ice-dammed	4045000	49.4
Dig Tsho	Himalaya (Nepal)	1999	Mool et al. (2001)	Moraine-dammed	500000	20.0
Godley	Southern Alps, New Zealand	1994	Warren and Kirkbride (1998)	Moraine-dammed	1650000	56.2
Godley	Southern Alps, New Zealand	1994	Allen et al. (2009)	Moraine-dammed	1700000	60.0
Gopang Gath	Himalaya (Himachal Pradesh)	2010	Worni et al. (2012)	Moraine-dammed	580000	30.0
Guangxiecuo Lake	Himalaya (Tibet)	1988	Jiang et al. (2004)	Moraine-dammed	272000	10.2
Hazard / Steele	Yukon, Canada	1974	Collins and Clarke (1977)	Ice-dammed	880000	16.0
Hazard / Steele	Yukon, Canada	1979	Clarke (1982)	Ice-dammed	1274000	15.5
Hidden Creek Lake	Alaska	1999-2000	Cunico (2003)	Ice-dammed	822492	25.8
Imja	Himalaya (Nepal)	1992	Fujita et al. (2009)	Moraine-dammed	600000	47.0
Imja	Himalaya (Nepal)	2002	Fujita et al. (2009)	Moraine-dammed	864000	41.6
Imja	Himalaya (Nepal)	2009	Sakai (2004, 2012)	Moraine-dammed	1010000	35.1
Imja	Himalaya (Nepal)	2012	Somos-Valenzuela et al. (2013)	Moraine-dammed	1210000	52.6
Ivory	Southern Alps, New Zealand	1986	Hicks et al. (1990)	Moraine-dammed	117931	23.7
Ivory	Southern Alps, New Zealand	1976	Hicks et al. (1990)	Moraine-dammed	73000	21.3
Ivory	Southern Alps, New Zealand	1980	Hicks et al. (1990)	Moraine-dammed	98414	20.5
Lake No Lake	British Columbia, Canada	1999	Geertsema and Clague (2005)	Ice-dammed	5000000	150.0
Leones	North Patagonia	2001	Harrison et al. (2008); Loriaux and Casassa (2013)	Moraine-dammed	19501000	125.9

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Longbasaba	Himalaya (Tibet)	2009	Yao et al. (2012)	Moraine-dammed	1218700	48.0
Maud Lake	Southern Alps, New Zealand	1994	Allen et al. (2009)	Moraine-dammed	1300000	60.0
Miage	Alps, Italy	2003	Diolaiuti et al. (2005)	Ice-dammed	35900	9.5
Mt Elbrus	Caucasus, Russia	2000	Petrakov et al. (2007)	Ice-dammed; supraglacial	89000	6.2
MT Lake	British Columbia, Canada	1982-3	Blown and Church (1985)	Moraine-dammed	41600	11.9
Mueller	Southern Alps, New Zealand	2002	Allen et al. (2009)	Moraine-dammed; supraglacial	500000	8.6
Nef	North Patagonia	1998?	Loriaux & Casassa (2013); Warren et al. (2001)	Moraine-dammed	5133000	150.1
Ngozumpa	Himalaya (Nepal)	2009	Thomson et al. (2012)	Moraine-dammed; supraglacial	300000	10.0
Ngozumpa 2	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	185100	21.7
Ngozumpa 3	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	427900	25.3
Ngozumpa 4	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	572900	27.4
Petrov Lake	Tien Shan	1978	Sevast'yanov and Funtikov (1981); Loriaux and Casassa (2013)	Moraine-dammed; supraglacial	1630000	12.3
Petrov Lake	Tien Shan	2003	Engel et al. (2012)	Moraine-dammed; supraglacial	3660000	14.6
Petrov Lake	Tien Shan	2006	Janský et al. (2010)	Moraine-dammed; supraglacial	3905000	15.4
Petrov Lake	Tien Shan	2006	Engel et al. (2012)	Moraine-dammed; supraglacial	3800000	15.6
Petrov Lake	Tien Shan	2008	Engel et al. (2012)	Moraine-dammed; supraglacial	3880000	16.0
Petrov Lake	Tien Shan	2009	Janský et al. (2009); Loriaux and Casassa (2013)	Moraine-dammed; supraglacial	3900000	16.4
Pida	Himalaya (Tibet)	2005	Xin et al. (2008)	Moraine-dammed	970000	52.0
Spong Togpo	Himalaya (Jammu and Kashmir)	2010	Worni et al. (2012)	Moraine-dammed	150000	12.0
Tulsequah	British Columbia, Canada	1958	Marcus (1960)	Ice-dammed	3861900	60.9
Zanam C	Himalaya (Bhutan)	2008	Fujita et al. (2012)	Moraine-dammed	160000	10.6

Supplementary Table 2: Compiled dataset of glacial lake areas and volumes.

Glacier or Lake	Location	Survey date	Study	Dam Type / Lake Context	Lake Area (m^2)	Volume (x 10^6 m^3)
Abmachimai Co	Himalaya (Tibet)	1987	Sakai (2004, 2012)	Moraine-dammed	560000	19
Ape Lake	British Columbia, Canada	1984-85	Gilbert and Desloges (1987)	Ice-dammed	2770606	92.78
Bashkara	Caucasus, Russia	2005?	Petrokov et al. (2007)	Moraine-dammed	65000	0.74
Bashkara	Caucasus, Russia	2008	Petrokov et al. (2011)	Moraine-dammed	85000	1
Briksdalsbreen	Norway	1979	Duck and McManus (1985)	Moraine-dammed	47100	0.314
Briksdalsbreen	Norway	1982	Duck and McManus (1985)	Moraine-dammed	45300	0.282
Cachet II	North Patagonia	2008-9	Casassa et al. (2010), Loriaux & Casassa (2013)	Ice-dammed	4045000	200
Chamlang south	Himalaya (Nepal)	2009	Sawagaki et al. (2012)	Moraine-dammed	870000	35.6
Checquiacocha	Cordillera Blanca, Peru	2008	Emmer and Vilimek (2013)	Moraine-dammed	351600	12.855
Dig Tsho	Himalaya (Nepal)	1999	Mool et al. (2001)	Moraine-dammed	500000	10
Gelhaipuco	Tibet	1987-8	Mool et al. (2001), Yao et al. (2012)	Moraine-dammed	548000	25.5
Goddard	British Columbia, Canada	1994	Clague and Evans (1997)	Ice-dammed	210000	4
Godley	Southern Alps, New Zealand	1994	Warren and Kirkbride (1998)	Moraine-dammed	1650000	85.72
Godley	Southern Alps, New Zealand	1994	Allen et al. (2009)	Moraine-dammed	1700000	102
Hazard / Steele	Yukon, Canada	1974	Collins and Clarke (1977)	Ice-dammed	880000	14
Hazard / Steele	Yukon, Canada	1979	Clarke (1982)	Ice-dammed	1274000	19.62
Hidden Creek Lake	Alaska	1999-2000	Cunico (2003)	Ice-dammed	822492	21.23
Hooker	Southern Alps, New Zealand	1995	Allen et al. (2009)	Moraine-dammed	700000	41
Hooker	Southern Alps, New Zealand	2002	Allen et al. (2009)	Moraine-dammed	900000	59
Hooker	Southern Alps, New Zealand	2009	Robertson et al. (2013)	Moraine-dammed	1220000	50
Imja	Himalaya (Nepal)	1992	Fujita et al. (2009)	Moraine-dammed	600000	28
Imja	Himalaya (Nepal)	2002	Fujita et al. (2009)	Moraine-dammed	864000	35.8
Imja	Himalaya (Nepal)	2009	Sakai (2004, 2012)	Moraine-dammed	1010000	35.5
Imja	Himalaya (Nepal)	2012	Somos-Valenzuela et al. (2013)	Moraine-dammed	1210000	63.8
Imja	Himalaya (Nepal)	2012	Somos-Valenzuela et al. (2014)	Moraine-dammed	1257000	61.6

Ivory	Southern Alps, New Zealand	1986	Hicks et al. (1990)	Moraine-dammed	73000	1.45
Ivory	Southern Alps, New Zealand	1976	Hicks et al. (1990)	Moraine-dammed	98414	2.02
Ivory	Southern Alps, New Zealand	1980	Hicks et al. (1990)	Moraine-dammed	117931	3.52
Laguna Safuna Alta	Cordillera Blanca, Peru	2001	Hubbard et al. (2005)	Moraine-dammed	343152	21.3
Lake No Lake	British Columbia, Canada	1999	Geertsema and Clague (2005)	Ice-dammed	5000000	720
Lapa	Caucasus, Russia	2006	Petrakov et al. (2007)	Moraine-dammed	28000	0.143
Lapa	Caucasus, Russia	2010	Petrakov et al. (2011)	Moraine-dammed	40000	0.2
Leones	North Patagonia	2001	Harrison et al. (2008), Loriaux and Casassa (2013)	Moraine-dammed	19501000	2454.61
Llaca	Cordillera Blanca, Peru	2004	Emmer and Vilimek (2013)	Moraine-dammed	44000	0.274
Longbasaba	Himalaya (Tibet)	2009	Yao et al. (2012)	Moraine-dammed	1218700	64
Lower Barun	Himalaya (Nepal)	1993	Sakai (2004, 2012)	Moraine-dammed	600000	28
Lugge	Himalaya (Bhutan)	2002	Sakai (2004, 2012)	Moraine-dammed	1170000	58.3
Maud Lake	Southern Alps, New Zealand	1994	Allen et al. (2009)	Moraine-dammed	1300000	78
Miage	Alps, Italy	2003	Diolaiuti et al. (2005)	Ice-dammed	35900	0.34
Mt Elbrus	Caucasus, Russia	2000	Petrakov et al. (2007)	Ice-dammed; supraglacial	89000	0.55
MT Lake	British Columbia, Canada	1982-3	Blown and Church (1985)	Moraine-dammed	41600	0.496
Mueller	Southern Alps, New Zealand	2002	Allen et al. (2009)	Moraine-dammed; supraglacial	500000	4.3
Mueller	Southern Alps, New Zealand	2009	Robertson et al. (2012)	Moraine-dammed; subaqueous ice ramp	870000	20
Nef	North Patagonia	1998?	Loriaux & Casassa (2013), Warren et al. (2001)	Moraine-dammed	5133000	770.71
Ngozumpa	Himalaya (Nepal)	2009	Thomson et al. (2012)	Moraine-dammed; supraglacial	300000	2.2
Ngozumpa 2	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	185100	3.296
Ngozumpa 3	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	427900	10.573
Ngozumpa 4	Himalaya (Nepal)	2008	Sharma et al. (2012)	Moraine-dammed	572900	77.3
Palcacocha	Cordillera Blanca, Peru	2009	Emmer and Vilimek (2013)	Moraine-dammed	528400	17.325
Palcacocha	Cordillera Blanca, Peru	2009	Somos-Valenzuela and McKinney (2011)	Moraine-dammed	518426	17.33

Paqu Co	Himalaya (Tibet)	1987	Sakai (2004, 2012)	Moraine-dammed	310000	6
Petrov Lake	Tien Shan	1978	Sevast'yanov and Funtikov (1981); Loriaux and Casassa (2013)	Moraine-dammed; supraglacial	1630000	20
Petrov Lake	Tien Shan	2003	Engel et al. (2012)	Moraine-dammed; supraglacial	3660000	53.4
Petrov Lake	Tien Shan	2006	Janský et al. (2010)	Moraine-dammed; supraglacial	3905000	60.309
Petrov Lake	Tien Shan	2006	Engel et al. (2012)	Moraine-dammed; supraglacial	3800000	59.2
Petrov Lake	Tien Shan	2008	Engel et al. (2012)	Moraine-dammed; supraglacial	3880000	62
Petrov Lake	Tien Shan	2009	Janský et al. (2009), Loriaux and Casassa (2013)	Moraine-dammed; supraglacial	3900000	63.96
Quangzonk Co	Himalaya (Tibet)	1987	Sakai (2004, 2012)	Moraine-dammed	760000	21.4
Quitacocha	Cordillera Blanca, Peru	2011	Emmer and Vilimek (2013)	Moraine-dammed	130400	3.232
Rajucolta	Cordillera Blanca, Peru	2004	Emmer and Vilimek (2013)	Moraine-dammed	512700	17.546
Raphsthren, Bhutan	Himalaya (Bhutan)	1984	Sakai (2004, 2012)	Moraine-dammed	1380000	66.83
Tam Pokhari	Himalaya (Tibet)	1992-3	Mool et al. (2001), Yao et al. (2012)	Moraine-dammed	470000	21.3
Tararhua	Cordillera Blanca, Peru	2008	Emmer and Vilimek (2013)	Moraine-dammed	358000	4.238
Tasman	Southern Alps, New Zealand	2009	Robertson et al. (2012)	Moraine-dammed	5960000	510
Thulagi	Himalaya (Nepal)	1995	Sakai (2004, 2012)	Moraine-dammed	760000	31.8
Thulagi	Himalaya (Nepal)	2009	Sakai (2004, 2012)	Moraine-dammed	940000	35.37
Tsho Rolpa	Himalaya (Nepal)	1993	Sakai (2004, 2012)	Moraine-dammed	1390000	76.6
Tsho Rolpa	Himalaya (Nepal)	2009	Chikita et al. (1999), Sakai (2004, 2012)	Moraine-dammed	1540000	85.94
Tulsequah	British Columbia, Canada	1958	Marcus (1960)	Ice-dammed	3861900	229