**ESRIN/RFQ/3-13731/12/I-BG**

# Slope stability and Glacial LAke Monitoring Service
# http://sglamo.gamma-rs.ch

# Executive Summary

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Authors
Andreas Wiesmann, Tazio Strozzi, Rafael Caduff
Gamma Remote Sensing, Switzerland

Holger Frey and Christian Huggel
Department of Geography, University of Zurich, Switzerland

Eva Mätzler, Jakob Abermann, Dorthe Petersen
ASIAQ, Greenland

Andreas Kääb
Department of Geosciences, University of Oslo, Norway

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# 1. INTRODUCTION

S:GLA:MO (Slope Stability and Glacial Lake Monitoring) was an ESA funded project (ESRIN/Contract No. 4000110404/14/I-BG) lead by GAMMA Remote Sensing AG, Switzerland, in collaboration with the Department of Geography, University of Zurich, Switzerland, ASIAQ, Greenland, and the Department of Geosciences, University of Oslo, Norway. The aim of the project was to implement and provide a service that provides an integrated assessment of hazards related to glacier lakes that addresses the widely acknowledged dependencies, integrated detection, monitoring and modelling of glacier lakes together with detection, monitoring and modelling of slope instabilities and glacier conditions and behaviour that potentially affect the glacier lakes. The service was developed in close collaboration with scientific, commercial, governmental, and non-governmental users

# 2. WHY DO WE NEED A SERVICE FOR GLACIER LAKE MONITORING?

Glaciers are retreating all over the world with very few exceptions and mountain permafrost is degrading, due to continued atmospheric warming. These trends and the magnitude of changes reach now or exceed already historical limits and will continue under all reasonable climate scenarios. These developments change hazard potentials. Whereas some glacier-related hazard potentials might actually decrease as a consequence of glacier retreat, new lakes will develop and existing lakes will expand. As a consequence, the probability for glacier lake outburst floods (GLOF) will increase. Not only the probability but as function of the potentially increased water volume as well the intensity of glacier lake outburst will rise. Due to the farther reach of GLOFs compared to other glacier related mass movements, the formation of new lakes implies an expansion of the hazard zone potentially affected by glacial hazards. Importantly, resulting disasters are typically a result of process interactions and chain reactions involving also other processes than those directly related to the water stored in the lakes, such as slope instabilities above and below the lakes.

At the same time, the human presence in glacierised regions changes, and is intensified in many areas as a result of increased land-use, for instance for tourism, hydropower- and water-use, traffic, or exploration of ground resources. These developments change, in most cases increase, the vulnerability and exposure components of risk.

It therefore becomes clear that a rise in risks related to glacier lakes can be well expected for the coming decades coupled with a rising need for proper hazard and risk assessments. The related challenges are complicated by the fact that many of the natural developments do not have historic precursors so that hazard assessments based on historic empirical data and evidences are not sufficient anymore. Rather, such assessments need to be based on

- objective, integrative and transparent assessment schemes in order to be transferable and controllable;
- area wide mappings of conditions and processes (the domain of remote sensing) to fulfil the demand for an integrative assessment;

- a temporally transversal assessment perspective, including an assessment of the current situation and as well considering potential future developments;
- process models in order to anticipate potential chain reactions and process interactions.

The implemented S:GLA:MO service responds exactly to these modern requirements. All the demands of a modern glacier lake hazard assessment as described above are reflected in the 'checklist for glacier lake hazard assessment', developed in the framework of S:GLA:MO. This checklist should guide the responsible glacier hazard experts through all aspects and factors to be considered for an integrative, Earth observation (EO) based first-order hazard assessment of existing glacier lakes for both current and potential future conditions. ('First order' hazard assessment refers to an approach where in a first step, area-wide EO and regional-scale simulations are used to evaluate an entire area. This first step leads then to prioritizing a list of potentially critical situations. In further steps, these sites are then closer examined using more detailed EO, process simulations, and ground-based methods and reconnaissance). The checklist does not replace the geoscientific expertise of the assessor, but should prevent him from ignoring potentially important hazard components. The checklist follows the state-of-the-art as promoted by GAPHAZ, the scientific standing group of the IACS and IPA on Glacier and Permafrost hazards in Mountains.

## 3. WHAT IS THE AIM OF THE S:GLA:MO SERVICE

The aim of the S:GLA:MO service is to provide an assessment of GLOF related hazards based on EO-derived products, in-situ data and modelling results. The service is driven by user needs that were identified during ESA's Innovator2 GLOF project and during the initialisation of the S:GLA:MO service. The service fills the gap of interdisciplinary competence in the combined analysis of EO, in-situ data and hazard competence towards a GLOF related hazard assessment (Figure 1). Different higher level EO products can be selected for the assessment (Figure 2). The service provision is done by a consortium led by GAMMA Remote Sensing AG, Switzerland, The Department of Geography, University of Zurich, Switzerland, Asiaq, Greenland, and the Department of Geosciences, University of Oslo, Norway.

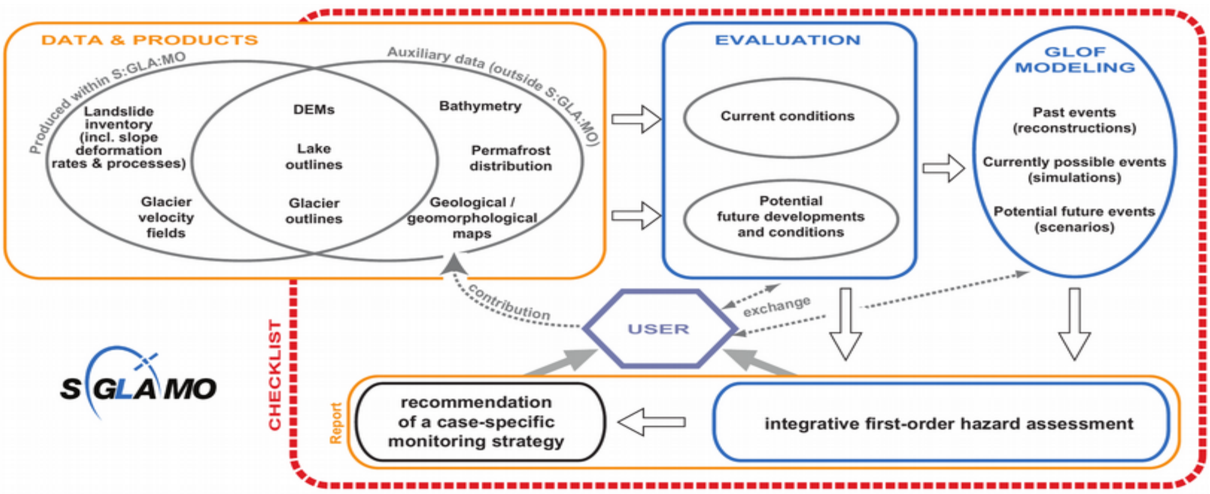


*Figure 1: S:GLA:MO assessment approach. The service is based on EO information, that is used combined with auxiliary data such as in-situ data and modelling results for a glacier lake related hazard assessment. The outcome is documented in the hazard assessment report.*

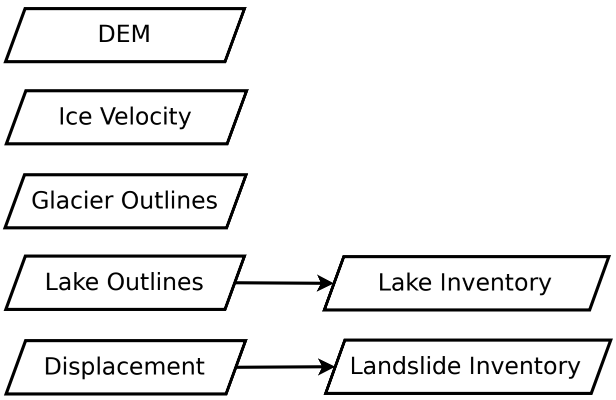


*Figure 2: Main EO products that feed into the hazard assessment report. If necessary higher level inventory products are made from the lake outlines and the displacement maps.*

## 4. WHAT IS THE S:GLA:MO SERVICE STRUCTURE?

The S:GLA:MO concept is set-up in a modular way so that it is flexible enough to cover different application cases but still is strict enough to ensure guidance, quality and objectivity of the service. Very important is the interaction with the user to address the different technical levels and competences and to ensure capacity building and sustainability. In that perspective the service is seen as an iterative (circular) process that can lead to new insights and needs. The cycle consists of 5 tasks and starts with a case definition, followed by the service initialisation, the production, the hazard assessment, and finally the product delivery and recommendations for future work (See also Table 1 for a more detailed outline). An important tool in the service management are check lists. The hazard assessment check list is a living document and updated with service evolution. The latest version is always available from the S:GLA:MO website http://sglamo.gamma-rs.ch. The authors view the development of the latter hazard assessment check list as a major outcome of S:GLA:MO as it allows for a transparent and, as much as possible, objective integrative hazard assessment, not least including the use of EO data for this purpose.

*Table 1: Check-list for the S:GLA:MO service.*

| *Service Task* | *Description* |
|---|---|
| Case | A case of GLOF hazard shall be addressed by the S:GLA:MO service. The consortium is either approached by a potential user or approaches a potential user for the implementation of the service. We define a case as the availability of:<br>1. User<br>2. Test area<br>3. Open questions related to GLOF<br>4. Funding |
| Initialisation | In the initialisation phase the service implementation is discussed together with the user. As the service needs to be adapted to different users and scenarios, it is important that a common understanding for the open questions and the answers that can be delivered is reached. The threat-checklist of the synthesis report can be used here. The following points need to be addressed:<br>1. Consolidation of user needs/questions<br>2. Consolidation of the information the S:GLA:MO service can provide<br>3. Definition of contacts and communication<br>4. Definition of the necessary products (EO products, modelling, auxiliary data):<br>◦ Necessary EO data<br>◦ Information the user can provide (auxiliary data, validation data)<br>◦ Timing<br>◦ Spatial resolution necessary<br>◦ Data formats<br>◦ Map projection<br>5. Work plan<br>6. Budget |
| Production | The production, validation and uncertainty characterisation of the selected products and modelling is following the established processing lines implemented by the partners. The task includes:<br>1. Ordering of necessary EO data<br>2. Ordering of additional auxiliary data, if necessary<br>3. Production<br>4. Validation and uncertainty characterisation<br>5. Delivery of products for hazard assessment |
| Assessment | Based on the products, the hazard assessment is done and documented in a report/checklist. The work steps are: |

| | |
|---|---|
| | 1. Hazard assessment based on the products and potentially additional (auxiliary) information<br>2. Recommendations for future work and service improvements<br>3. Document findings in a report/checklist<br>4. Review assessment report |
| Delivery | It is important to not just deliver the report/checklist but also discuss the findings with the user and find out if further needs for additional or updated information exist. Depending on the technological level of the user, capacity building might be helpful. The work steps are:<br>1. Deliver hazard assessment report to the user<br>2. Discuss hazard assessment report with the user<br>3. Discuss potential future work with the user |

## 5. WHAT ARE THE S:GLA:MO PRODUCTS?

The main S:GLA:MO product is the hazard assessment report. It is written and structured following the «Hazard Assessment Checklist». The EO derived products and modelling results used within the report (intermediate products) can also be delivered to the service user. The main intermediate EO products are described below.

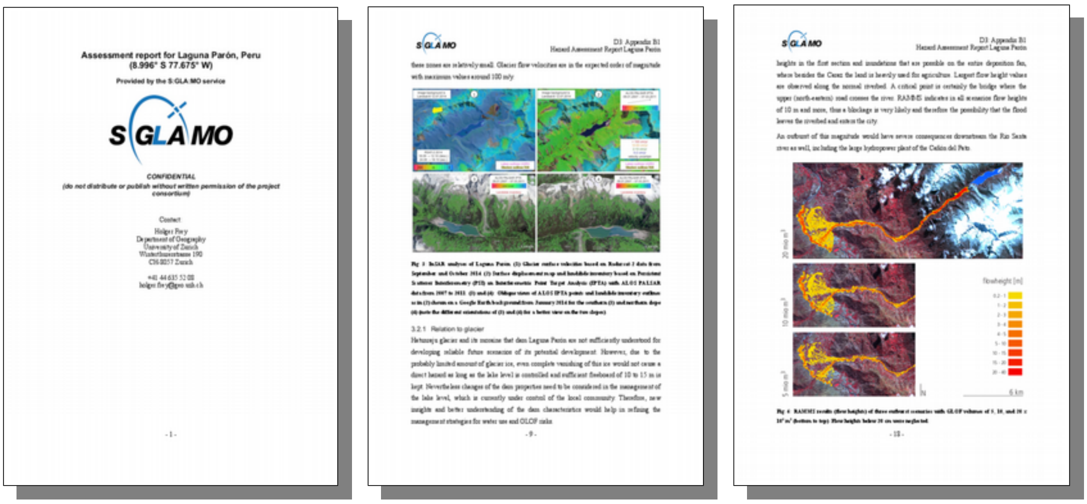
Assessment report for Laguna Parón, Peru
(8.996° S 77.675° W)
Provided by the S:GLA:MO service
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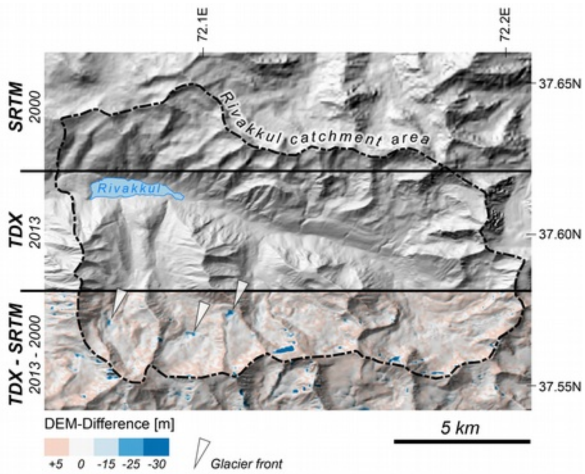
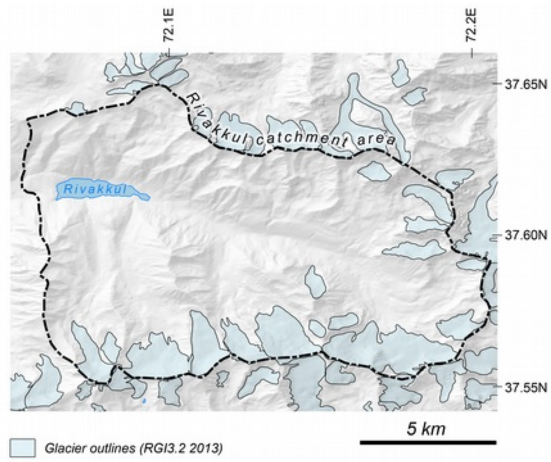
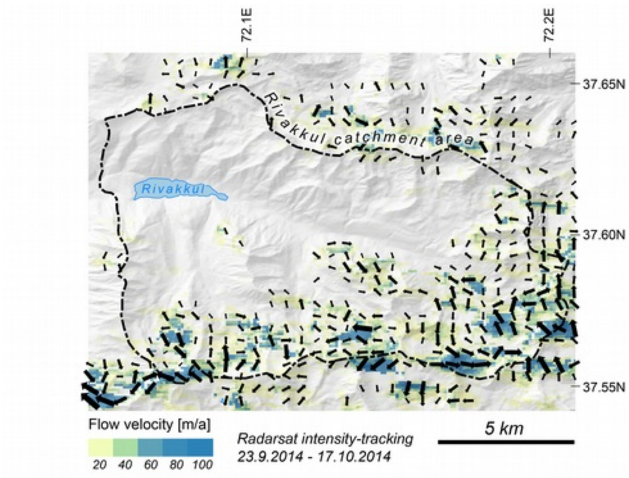
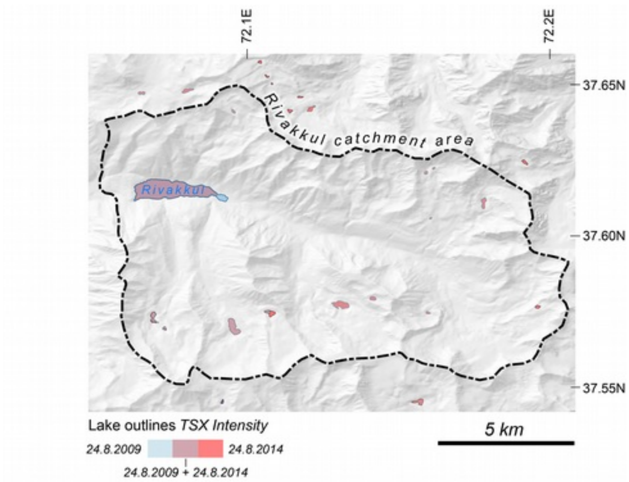
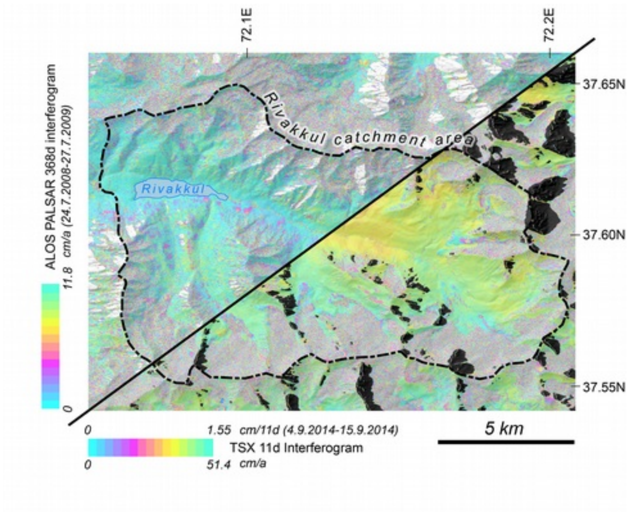
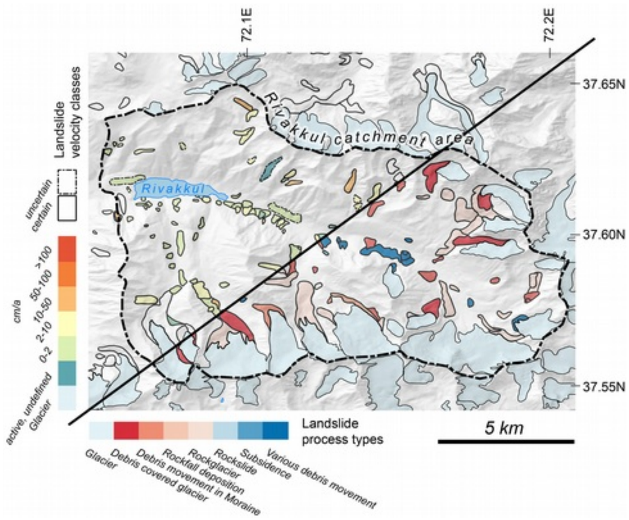
*Figure 3: Selected pages of the Hazard Assessment Report of Laguna Paron.*

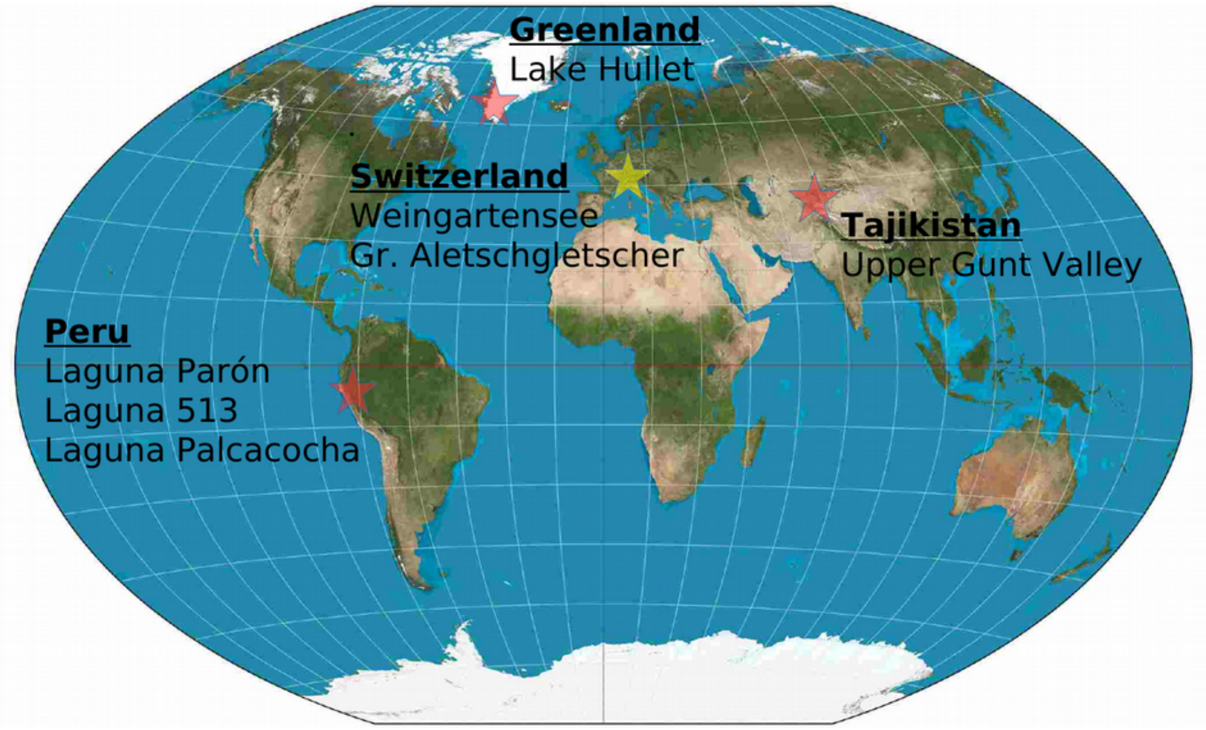
*Table 2: Use and role of EO data in S:GLA:MO*

| **Product** | **Specific role of EO data in the case studies** |
|---|---|
| *DEM* (surface topography)<br>*Height change* (e.g. evolution of thickness of ice dam)<br> | Base information for all information layers used for orthorectification.<br>Crucial parameter for assessing dam stability.<br>Used for the modelling of potential outburst floods (Parón). Very valuable for the user for other purposes (outside S:GLA:MO).<br>Different possibilities for acquisition, but InSAR provides a very good cost-quality balance, in particular for the described purpose. |
| *Glacier outlines*<br> | Required for assessing the influence and interactions of smaller upstream lakes with glaciers.<br>Required for the modelling of the glacier bed topography.<br>Helpful for assessing lake-glacier interactions, glacier fluctuations in the recent past, and required for other products (surface velocities, bed topography, etc.). |

| Product | Specific role of EO data in the case studies |
|---|---|
| *Glacier surface velocities*<br><br> | Provides insights on glacier dynamics and has a high scientific value, also for the user (outside the scope of S:GLA:MO)<br>Important to understand near-future development of ice dam as ice dam thickness is a function of ice flux and glacier ablation.<br>Indicator for the state of activity of glaciers calving into smaller upstream lakes. |
| *Lake detection* (SAR, optical)<br><br> | Important for detecting small upstream lake. Some of these lakes are highly dynamic, but potentially critical for the hazard situations (e.g. supraglacial lakes).<br>Useful for estimating lake volume (changes) and outburst events at times without ground measurements (e.g. before those started or in case of failure). |

| Product | Specific role of EO data in the case studies |
|---|---|
| *Slope instabilities*<br><br> | It is important to detect the absence of slope instabilities directly above the lakes or within the lake dams.<br>Important to detect in the up- and downstream areas to anticipate potential chain reactions leading to or aggravating an outburst flood<br>Observed slope instabilities at moraines surrounding a lake help to guide on-site geophysical field investigations, which in turn complement the InSAR-based information (e.g. regarding depth of the movements). |
| *Landslide Inventory*<br><br> | Added value product based on the slope instabilities product.<br>Important to detect the absence of slope instabilities directly above the lakes or within the lake dams.<br>Important to detect in the up- and downstream areas to anticipate potential chain reactions leading to or aggravating an outburst flood.<br>The rock glaciers / permafrost creep detected indicated locations where ground ice could be involved in the damming of up-stream lakes and where thus atmospheric warming could impact dam stability. |

# 6. WHERE HAS THE S:GLA:MO SERVICE BEEN APPLIED?




The S:GLA:MO service has been successfully implemented for cases in Switzerland, Greenland, Peru and Tajikistan. The service protocol proved to be consistent and the service was run along the specifications and protocol. The modularity of the service made it possible to apply the same protocol for the quite different test cases, including Arctic lakes dammed by the ice-sheet, mountain glacier lakes, and potential future lakes that do not yet exist. Several novel procedures (checklist, integral validation) were developed within S:GLA:MO and successfully tested and implemented using the three cases. The service can now be considered well established and can be deployed as it is for further sites in the future.

In all S:GLA:MO case studies, EO data, results and monitoring turned out essential for the hazards assessments and contributed results that the users were not aware of or not to the extent demonstrated. In our view, S:GLA:MO and many other studies show that EO data are very useful in regional-scale hazard assessments related to glacier lakes, in particular by providing constraints and reality to simulations. They also provide context in objective, integrative and transparent assessments..

# 7. WHAT ARE THE BENEFITS OVER EXISTING SERVICES AND SERVICE LIMITATIONS?

The generalised procedures implemented in the S:GLA:MO service allow the service to be applied to any case in the world. Checklists, roles, and standardised lines of actions developed and tested at the different stages of the service development ensure state-of-the-art data product generation, interpretation, and lake hazard assessment procedures. There are no other standardized services for EO-based, integrative assessments of glacier lakes hazards.

Clearly EO and models are not able to collect necessarily all information required for a thorough assessment, such as subsurface conditions, for example ice content of permafrost, or lake bathymetry. Also, the spatial and temporal resolution of available EO data, and their other characteristics, might not be adequate for the processes to be monitored; lake drainage events might be missed, topographic data for key dates not available, the necessary product accuracy not be reached, etc. The S:GLA:MO case studies provide good examples for such factors.

# 8. FURTHER READING

Emmer, A. & Vilimek, V. 2014. New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru. *Hydrology and Earth System Sciences* 18 : 3461–3479. DOI: 10.5194/hess-18-3461-2014-supplement

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. & Paul, F. 2010. A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards and Earth System Sciences* 10 : 339–352.

Frey, H., Huggel, C., Paul, F. & Haeberli, W. 2010. Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials. *Grazer Schriften der Geographie und Raumforschung, Proceedings of the 10th International Symposium on High Mountain Remote Sensing Cartography, held in Kathmandu, Nepal 8-11 September 2008* 45 :.

Gruber, F.E. & Mergili, M. 2013. Regional-scale analysis of high-mountain multi-hazard and risk indicators in the Pamir (Tajikistan) with GRASS GIS. *Natural Hazards and Earth System Sciences* 13 : 2779–2796.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D. & Richardson, S. 2004. An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotech Journal* 41 : 1068–1083.

Huggel, C., Kääb, A., Haeberli, W. & Krummenacher, B. 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. *Natural Hazards and Earth System Sciences* 3 : 647–662.

Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., Salzmann, N., Schmutz, K., Schneider, D., Strozzi, T. & Weidman, Y. 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences* 5 : 527–554.

Mergili, M. & Schneider, J.F. 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. *Natural Hazards and Earth System Science* 11 : 1447–1462. DOI: 10.5194/nhess-11-1447-2011

Richardson, S. & Reynolds, J. 2000. An overview of glacial hazards in the Himalayas. *Quaternary International* 65-66 : 31–47.

Schaub, Y., Haeberli, W., Huggel, C., Künzler, M. & Bründl, M. 2013. Landslides and new lakes in deglaciating areas: a risk management framework. In *Landslide Science and Practice: Social and Economic Impact and Policies*. C. Margottini, P. Canuti, & K. Sassa, eds. Berlin Heidelberg: Springer, pp. 31–38. DOI: 10.1007/978-3-642-31313-4_5

Schneider, D., Huggel, C., Cochachin, A., Guillén, S. & García, J. 2014. Mapping hazards from glacier lake outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru. *Advances in Geosciences* 35 : 145–155. DOI: 10.5194/adgeo-35-145-2014

Somos-Valenzuela, M.A., Chisolm, R.E., Rivas, D.S., Portocarrero, C. & McKinney, D.C. 2016. Modeling glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru. *Hydrology and Earth System Sciences Discussions* 1–61. DOI: 10.5194/hess-2015-512-AC2

Strozzi, T., Delaloye, R. & Kääb, A. 2010. Combined observations of rock mass movements using satellite SAR interferometry, differential GPS, airborne digital photogrammetry, and airborne photography interpretation - Strozzi - 2010 - Journal of Geophysical Research: Earth Surface (2003–2012) - Wiley Online Library. ... *: Earth Surface (2003* ….

Strozzi, T., Wiesmann, A., Kääb, A., Joshi, S. & Mool, P. 2012. Glacial lake mapping with very high resolution satellite SAR data. *Natural Hazards and Earth System Science* 12 : 2487–2498. DOI: 10.5194/nhess-12-2487-2012

Vilimek, V., Zapata, M., Klimes, J., Patzelt, Z. & Santillan, N. 2005. Influence of glacial retreat on natural hazard of the Palcacocha Lake area, Peru. *Landslides* 2 : 107–115.

Worni, R., Huggel, C. & Stoffel, M. 2013. Glacial lakes in the Indian Himalayas — From an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Science of The Total Environment* 468-469 : 71–84. DOI: 10.1016/j.scitotenv.2012.11.043