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Formation of glacial lakes - a recent dynamic process in the Hohe Tauern National Park

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Abstract

Due to climate change in high alpine environments, the surface-topography in the vicinity of glaciers changes very rapidly and in the case where glaciers expose natural basins after their retreat, "new" glacial lakes emerge.

These dynamic processes are quite obvious in the Hohe Tauern Mountain Range, especially in the Stubach Valley and the Obersulzbach Valley, both situated in the Salzburgian part of the Hohe Tauern National Park.

Two proglacial lakes, Unterer Eisboden See and Obersulzbach See, have consequently been monitored by the Hydrological Service of Salzburg in cooperation with Salzburg University, Department of Geography & Geology since the early 90s.

Modern and classical methods e.g. multi-temporal (aerial) photography, orthophoto interpretation, repeated terrestrial laser-scanning, ground penetration radar as well as bathymetry were used in an interdisciplinary approach to document the development of the lakes in front of the termini of Stubacher Sonnblickkees and Obersulzbachkees.

Additionally, parameters like precipitation, temperature, water level, discharge and conductivity were registered in order to analyze the dominant on-going processes in the water cycle. Regular daily water level fluctuations and even a glacial lake outburst flood (GLOF) in July 2006 were monitored at Unterer Eisboden See.

In order to calculate suspended and solute sediment fluxes at Obersulzbach See, gauging stations to measure sediment concentrations and turbidity were also installed.

As both lakes also represent the development of new ecosystems, hydrobiological probing and monitoring were also started.

In order to estimate the maximum possible extension of the two pro glacial lakes, ground radar measurements were carried out and surface models were combined with bathymetry.

This interdisciplinary work on both the above mentioned lakes offers various possibilities to understand dynamic processes (e.g. the influence on the downstream hydrological and geomorphological system due to discharge modifications, suspended sediment trapping, decoupling effects and long term sediment storage) in protected areas under global change conditions.

Keywords

Proglacial, lake, climate change, discharge, sedimentation, Hohe Tauern, glacier

Introduction and aim

One of the main tasks of the Hydrological Service, which was founded in 1893, is to monitor and to analyse various components of the water cycle, including glaciers and lakes in high alpine regions.

In the Salzburgian part of the National Park Hohe Tauern a total of 191 lakes of various sizes (max. 270 ha) and depth (max. 56, 8 m) were identified and mapped. Approx. 50 % of these lakes are situated between 2,200 and 2,500 m above sea level, and only 11 are situated above 2,600 m a.s.l. Since the middle of the 19th century 37 new lakes have emerged where glaciers exposed natural basins after their retreat (SEITLINGER 1999).

However, opposite developments have been observed too, e.g. at Keesboden in the Obersulzbach Valley, where a shallow lake, discovered in 1880, disappeared in 1897 (RICHTER 1888, RUDEL 1911). More recently "Eissee", situated near to Hochfilleck (2,943 m) in Stubachtal, which has existed at least since the end of the 50s (SLUPETZKY 1997c), disappeared in very recent time (2012).

These on-going dynamic processes in the Stubach Valley and the Obersulzbach Valley have been monitored by the Hydrological Service of Salzburg in cooperation with Salzburg University, Department of Geography & Geology since the early 90s. (SLUPETZKY 1997a, 1997b, 1998, 2007; WIESENEGGER & SLUPETZKY 2009).

As new proglacial lakes have a great influence on the downstream hydrological and geomorphological system, due to discharge modifications, decoupling effects, sediment trapping and long term sediment storage, Unterer Eisboden See and Obersulzbach See have been investigated in order to monitor the proglacial lake development, to analyze associated impacts on the hydrological and geomorphological system (mainly Obersulzbach See) and to predict potential future developments (mainly Unterer Eisboden See).

Study sites

Obersulzbach Valley, situated in the south-west of the Province of Salzburg in the National Park Hohe Tauern, is drained by Obersulzbach, a north-facing tributary to the River Salzach. In this valley 11 lakes of various sizes are to be found within the limits of National Park Hohe Tauern (SEITLINGER 1999) and *Obersulzbach See* (Fig. 1 Map C), first described and named by H. Slupetzky in 1989, is located in the uppermost part of the Obersulzbach Valley. Around 60 % (2009) of the lake's total catchment (17.8 km²), which ranges from 2,200 to 3,662 m.a.s.l, are covered by glaciers (WIESENEGGER 2013).

Stubach Valley is also located in the south-west of the Province of Salzburg and altogether 21 lakes are situated within the boundaries of National Park Hohe Tauern (SEITLINGER 1999). The first signs of this new proglacial lake*Unterer Eisboden See* (Fig. 1 Map D), situated in the surroundings of Stubacher Sonnblickkees, were recognizable in 1987 and in 1990 it was surveyed by M. Kiskemper, Neubrandenburg and outlined on the map "Granatspitze" scale 1 : 5000 (SLUPETZKY 1997). Around 70 % (2009) of the lake's total catchment (1. 66 km²), which ranges from 2,500 to 3,088 m.a.s.l, are covered by glaciers (WIESENEGGER & SLUPETZKY 2009).

Methods

In order to monitor and analyze the ongoing processes at Unterer Eisboden See and Obersulzbach See, the following modern and classical methods were used:

- Multi-temporal (aerial) photography and orthophoto interpretation to map the spatio-temporal evolution of lakes following glacial retreat
- Geodetic survey to determine lake surface area (Unterer Eisboden See 1994)
- Repeated terrestrial laser-scanning (Obersulzbachkees since 2001, Stubacher Sonnblickkees since 2003) to quantify changes of the shore line as well as changes of other parameters (surface area).The spatial pattern of the retreat and the subsequent development of the lake were documented by means of terrestrial laser scanning and high resolutions DEMs were calculated.
- Repeated GPS surveys of the terminus of Stubacher Sonnblickkees and the shoreline of Unterer Eisboden See
- Measurement of yearly length variations of the glaciers within the long range program of the Austrian Alpine Club (ÖAV)
- Simple bathymetry by means of a perpendicular (Eisbodensee 1998)
- Bathymetry (echo sounding) using dGPS (Trimble Pathfinder ProXH) and echo-sounders (Furuno 4600) mounted on an inflatable boat to determine the max. lake-depth as well as the underwater geometry (Obersulzbach See 2009) and bathymetry combined with terrestrial laser scanning (Unterer Eisbodensee 2010)
- Subglacial DEMs based on ground penetrating radar measurements of Stubacher Sonnblickkees, terrestrial laser scans of the lake's shoreline and level as well as bathymetry carried out in 2010 in order to model the potential maximum lake surface
- Ground penetrating radar (GPR) to estimate sediment storage within the lakes, identify bedrock and thickness of glaciers (subglacial surface DEMs)
- Water temperature, water level and discharge registration at automatic gauging stations in order to analyze hydrological behavior of the lakes.
- Installation of a new automatic gauging station (named "Türkische Zeltstadt") at the outlet of Obersulzbach See, registering water level, water temperature and conductivity by the Hydrological Service in June 2009 in order to complement the already existing gauge "Kees" further downstream
- Hydrological sampling to assess sediment yields and synchronous sampling of sediment entering and leaving the lake. Suspended and solute sediment fluxes from the proglacial zone of the retreating Obersulzbachkees were quantified within a 20 month monitoring period (Jan 2010 to Sept 2011)
- Hydrobiological sampling to assess biocenosis and ecosystem development (currently only at Unterer Eisboden See)

Results

<u>Obersulzbach See</u>

Since the late 1980's ,due to the continuous retreat of Obersulzbachkees, which has receded more than 1,5 km in the last 60 years, a large and glacial over deepened bedrock basin has been exposed (GEILHAUSEN et al. 2012).

A shallow lake was first observed in 1989 at the glacier snout. The following lake development was heterogeneous, due to irregular retreat and downwaisting of the tongue of Obersulzbachkees (Fig 2) but the position of the lake's outflow remained constant.

A comparison of terrestrial laser scans shows that between 2009 and 2011 the surface area of the lake still increased in size (approx. 22,930 m²), mainly due to further glacial retreat at its southern end.

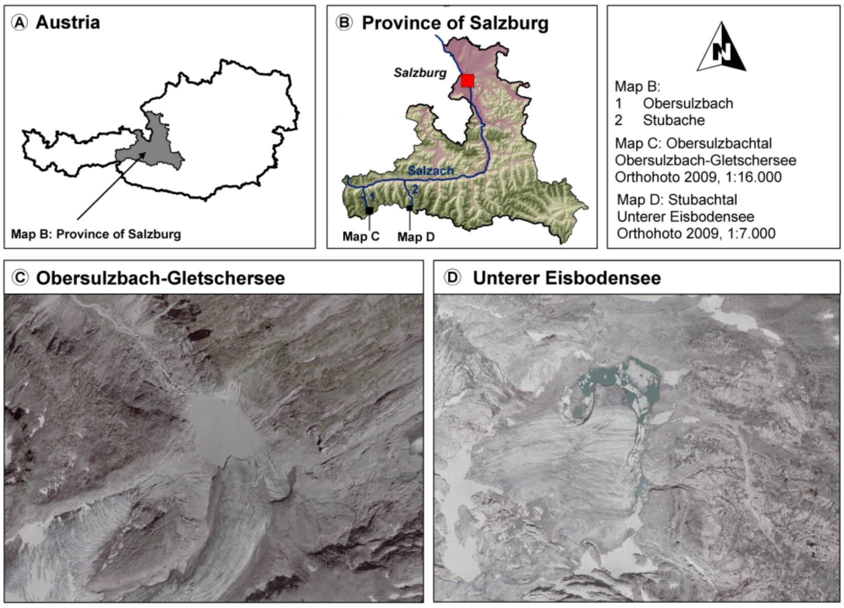

Figure 1: Location of the study sites

By means of the above mentioned methods, a maximum depth of 42 m and a volume of more than 2 Mio. m³as well as a surface area of approx. 95,000 m² were recorded. Other characteristic figures were: Max. length 460 m, max. width 295 m, mean depth 22 m, rel. depth (max. depth to mean diameter ratio) 12 (figures >4 indicate small deep lakes).

Below the water line the lake is characterized by steep slope gradients up to a depth of 30 m which then become less steep. Two flat basins, separated by a distinct ridge of 6 – 7 m in height, form the lake floor (KUM 2010).

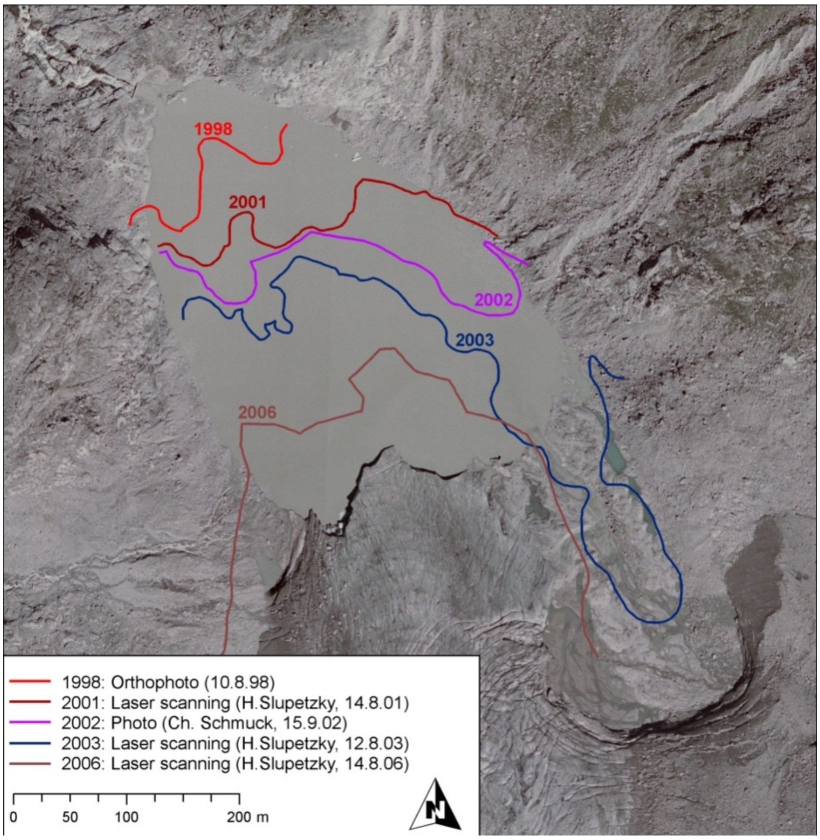

Figure 2: Glacier termini of the Obersulzbachkees, base map: orthophoto 2009

Figure 3: Bathymetry survey, Obersulzbach See July 2009, view to south.

GPR survey and lake floor morphology indicated that sediment storage in the lake is possible. The 20 month sediment monitoring showed that Obersulzbach See decouples coarse sediment transport and reduces the connectivity between glacial sediment production and downstream sediment fluxes. It diminishes suspended sediment concentrations (SSC) up to 88-95 %, prevents considerable decrease of SSCs at very low discharge and can shift its function within the suspended sediment cascade from a sink to a temporal source due to rain fall induced hill slope sediment supply (GEILHAUSEN et al. 2012a).

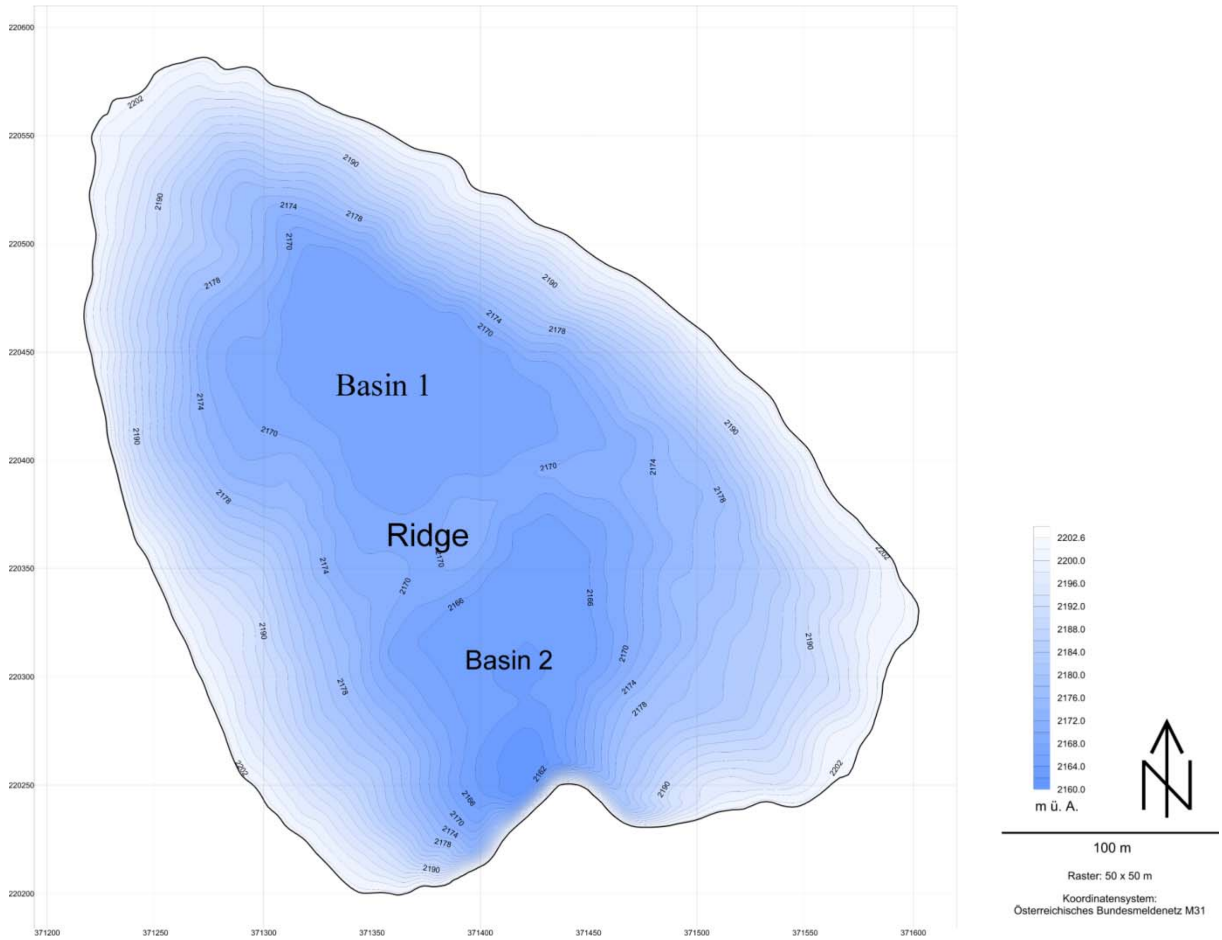

Figure 4: Bathymetry map of Obersulzbach See

Unterer Eisboden See

Due to glacial retreat, Unterer Eisboden See continuously increased its size during the following years (Fig. 5). The hydrological system of the lake was rather complex, in summer the water level was situated at 2,499 m a.s.l and the lake was mainly drained by its eastern outlet “Eislbach”, which functioned like an overspill. In autumn and winter, due to reduced meltwater intake from the glacier, the lake was mainly drained subglacially. Its level was lowered and “Keesbach”, situated at its southern end and approx. 6 m lower than Eislbach, functioned as the main outflow during this period.

In July 2006 a glacier outburst flood (GLOF), releasing approx. 100,000 m^3 within 3 days, was monitored. The outlet shifted subglacial to its present position and the water level of the lake dropped approx. 6 m (WIESENEGGER & SLUPETZKY 2009).

Results of the 2010 bathymetry, which was carried out to the order of the Hydro-logical service, showed a maximum depth of 20,3 m, mean depth 4,5 m, rel. depth (max. depth to mean diameter ratio) 10,2 (figures >4 indicate small deep lakes), a volume of approx. 140,000 m^3 and a surface area of approx. 31,000 m^2.

Below the water line the lake is characterized by steep slope gradients in the narrow southern part, whilst at the northern end slope gradients are very moderate (KUM 2011).

Table 1: Temporal development of characteristic figures of Unterer Eisboden See

	1994	1998	2003	2005	2008	2010
max. length [m]	80	132	200	200		370
max. width [m]	30	62	112	125	90	206
area in ha	0,470	0,627	1,417	1,90	2,0	3,10
max. depth [m]		7,8				20,3
volume [m^3]		12,340				138,550

A comparison of terrestrial laser scans shows that between 2010 and 2011 the surface area of Unterer Eisboden See still increased in size (approx. 8,000 m^2) and its shoreline (approx. 35 % consists of ice) became 100 m longer.

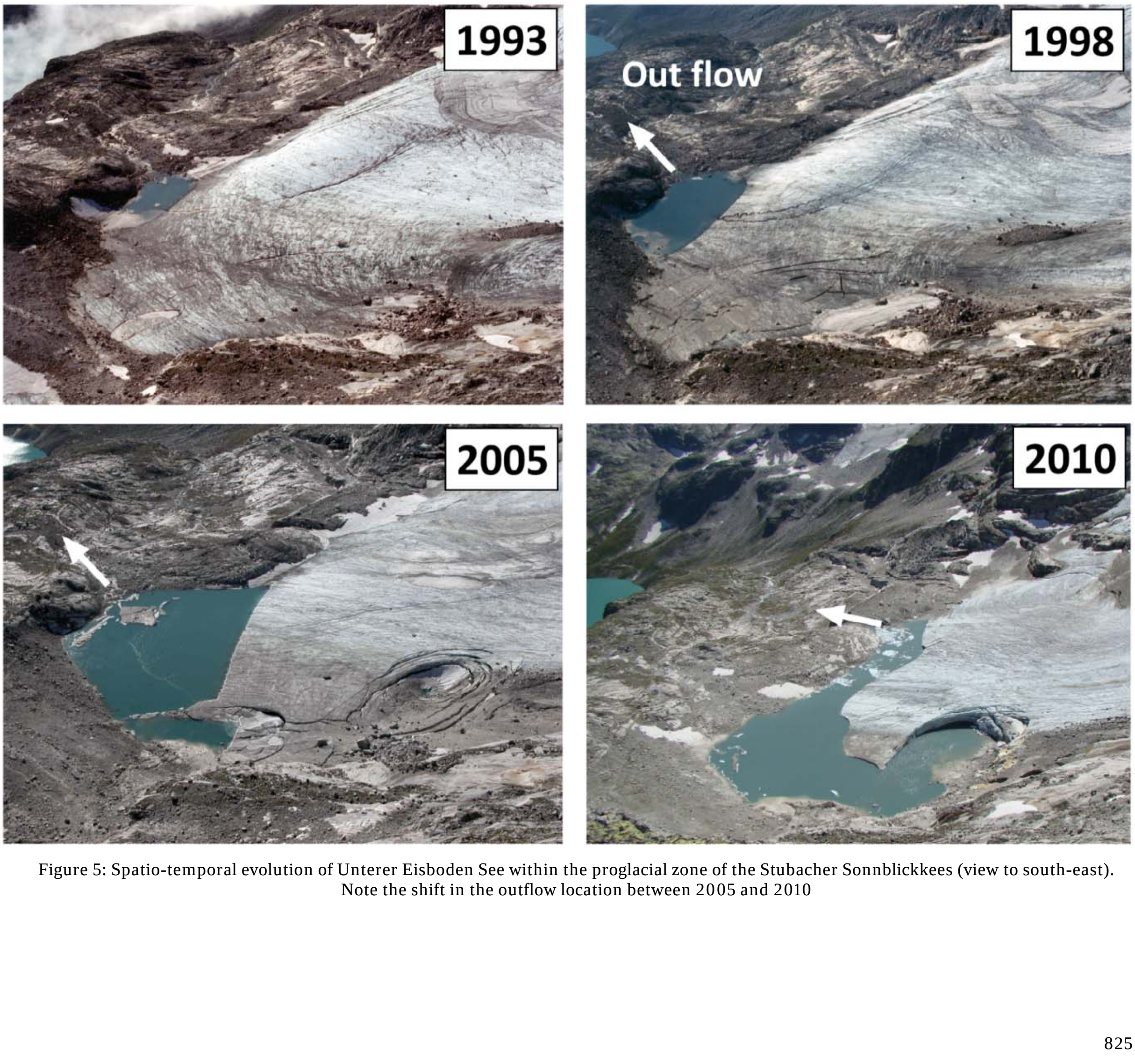

Figure 5: Spatio-temporal evolution of Unterer Eisboden See within the proglacial zone of the Stubacher Sonnblickkees (view to south-east). Note the shift in the outflow location between 2005 and 2010

In order to estimate the maximum potential lake surface area (Tab.2), two models, based on subglacial DEMs (Fig. 6) interpolated from GPR data and bathymetry, were used (GEILHAUSEN 2011).

Table 2: Possible future development of Unterer Eisboden See

Parameter	2010	Bedrock model	Sediment model
max. shoreline [m]	**1,362**	**1,480** (+111/-45)	**1,495** /+7/-5)
max. area [m²]	**31,050**	**74,790** (+644/-991)	**71,730** (+802/-824)
max. depth [m]	**20,3**	**22,3** (+/-0,4)	**22,3** (+/-0,4)
max. volume [m³]	**138,550**	**533,900** (+3920/-7735)	**497,130** (+5510/-5760)

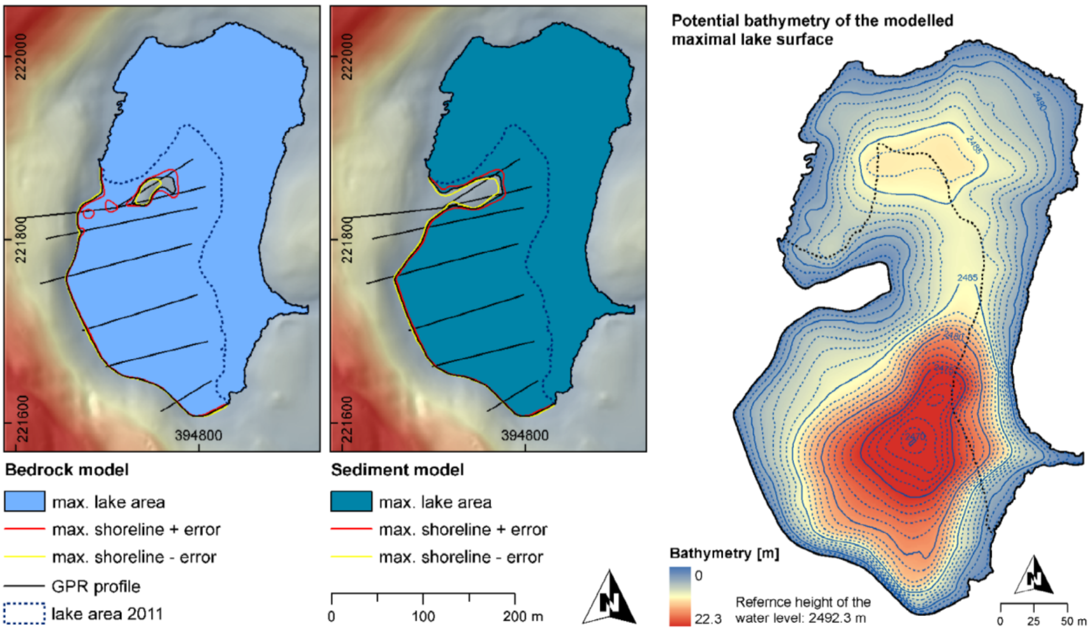

Figure 6: maximum potential lake area based on subglacial DEMs interpolated from GPR data and bathymetry.

Conclusion and perspectives

Obersulzbach See

At the moment, it is not clear whether Obersulzbach See has already reached its maximum size. On the one hand glacial outwash sands propagate into the lake and lake aggradation seems to be taking place, but on the other hand, the glacier is still retreating at the south end of the lake. Therefore, GPR measurements combined with high resolution terrestrial laser scanning are intended to clarify the course of the bedrock below the terminus of Obersulzbachkees, thus enabling an estimation of the possible maximum size of Obersulzbach See.

The monitoring of water temperature, conductivity, water level and discharge registration in order to analyze changes in the hydrological behavior of Obersulzbach See will be prolonged and hydrobiologicalmonitoring to assess the development of Obersulzbach See is planned.

At present, Obersulzbach See significantly reduces the connectivity between glacial sediment production and downstream sediment fluxes. The lake will be filled at least partly by sediments in the next decadesthereby changing its function in the sediment cascade from a sink to sediment storage with passage. In order to assess its potential trap efficiency on suspended sediments as well as to estimate the future development of the storage capacity, a two dimensional turbidity and velocity model, using on- site measurements along defined profiles in Obersulzbachsee, are intended. Furthermore, repeated bathymetry surveys in the near future are planned.

Unterer Eisboden See

Unterer Eisboden See showed interesting hydrological behavior and it took some time to understand the ongoing processes (sublacial drainage, shift of outlets, glacier outburst flood, rhythmical water level changes etc.).

The lake has achieved its permanent outlet situation and water level at 2,493 m a.s.l but it has not yet reached its potential maximum size. Model results show, that the lake could develop a max. area up to double the present size and contain 3 times as much water than at the moment. At present, the glacier is retreating at the south end of the lake but as GPR measurements show, there is still up to 35 m of ice which will be diminished by melting or calving in a view years.

The hydrological monitoring in order to analyze changes in the lake's behavior will be prolonged and hydrobiological monitoring and sampling will be repeated.

Unterer Eisboden See acts as a sediment trap and reduces the connectivity between glacial sediment production and downstream sediment fluxes. The volume of the lake will gradually be reduced by sediments in the next decades, but due to the Gneis bedrock and the morphology of the catchment, not as much as at Obersulzbach See. Repeated bathymetry surveys in the near future are planned to check this process.

Proglacial lake development

It is generally assumed that climate change and accelerated glacier melt will raise sediment discharge from proglacial zones. In the light of our findings, we address the topographic consequences of climate change with basin exposure and proglacial lake formation in expanding proglacial zones. A number of proglacial lakes have formed during the 20th century as a result of glacial retreat.

We, therefore, hypothesize an increasing likelihood that natural bedrock basins, capable of forming proglacial lakes, will be exposed in the Hohe Tauern National Park in the near future because many glaciers have receded in convergence zones of combining ice flows from multiple directions where glacier-bed over deepening is quite common.

As sediment load is both supply and hydraulically controlled and as such a sensitive parameter of environmental change, this raises the question of how the proglacial zone will take control on sediment yields if sediment production sites will be disconnected from the sediment transfer system. Scenarios of future sediment flux from any proglacial zone would depend critically on the potential development of a proglacial lake.

GIS based modelling of the subglacial topography in the Austrian Alps is subject to recent research and the National Park Hohe Tauern is certainly a point of interest.

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